Kavli Institute
for Cosmological Physics
at The University of Chicago

The Characterization of the Gamma-Ray Signal from the Central Milky Way

Tim Linden

along with:

Tansu Daylan, Doug Finkbeiner, Dan Hooper,
Stephan Portillo, Nick Rodd, Tracy Slatyer
Eric Carlson, Ilias Cholis

arXiv: 1402.6703
1407.5583
1407.5625
1409.1572

Joint IBS/MultiDark Workshop 2014- October 10, 2014

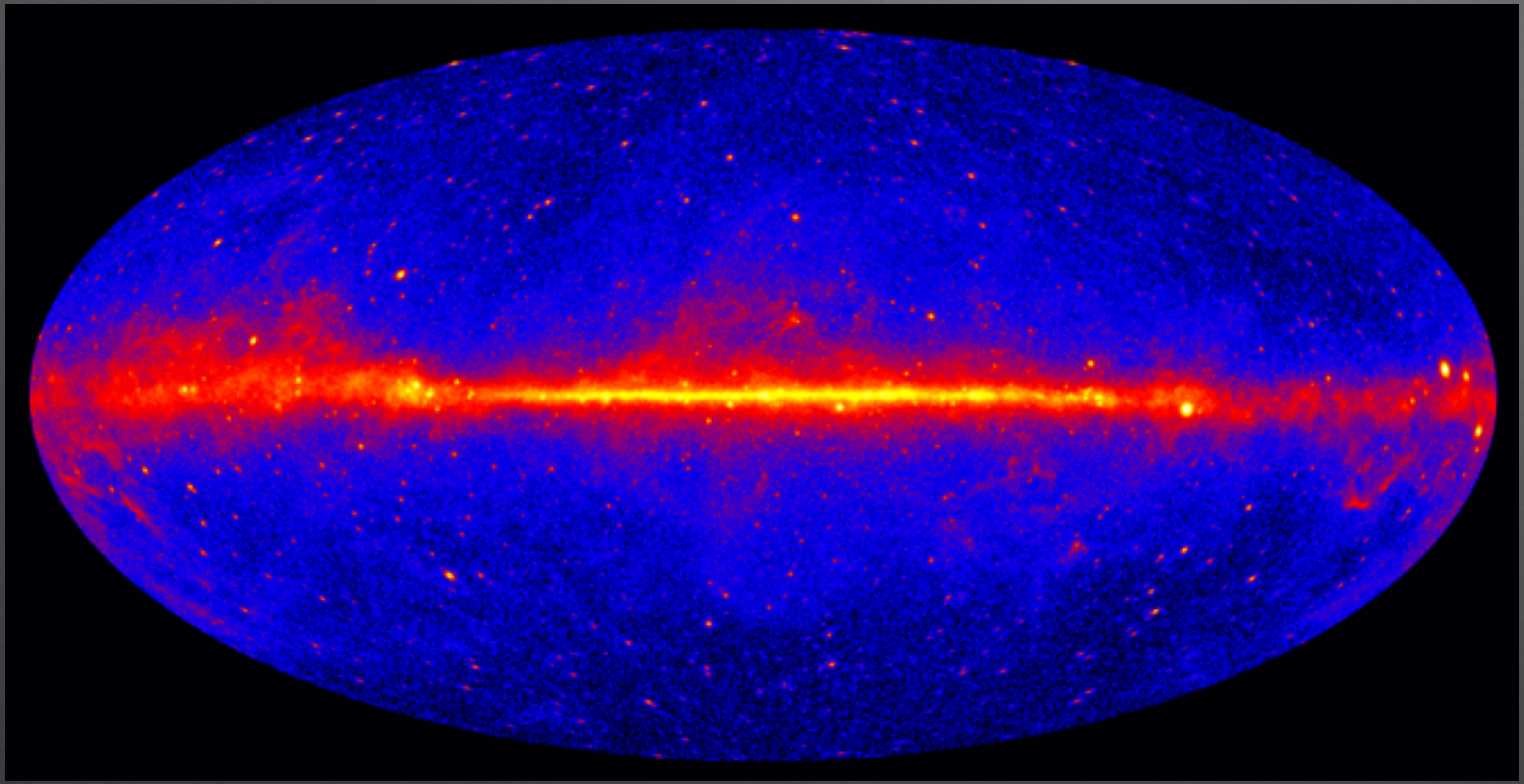
The Galactic Center

- Total Observed Gamma-Ray Flux from 1-3 GeV within 1° of the GC is ~1 x 10^{-10} erg cm^{-2} s^{-1}

- The flux expected from a vanilla dark matter model (100 GeV -> bb with an NFW profile) is ~2 x 10^{-11} erg cm^{-2} s^{-1}

- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the most naive prediction from dark matter simulations

Gamma-Ray Backgrounds



Point Sources

Pulsars

Blazars/AGN

Star Forming Galaxies

Supernova Remnants

Unidentified

Extragalactic (Isotropic) Background

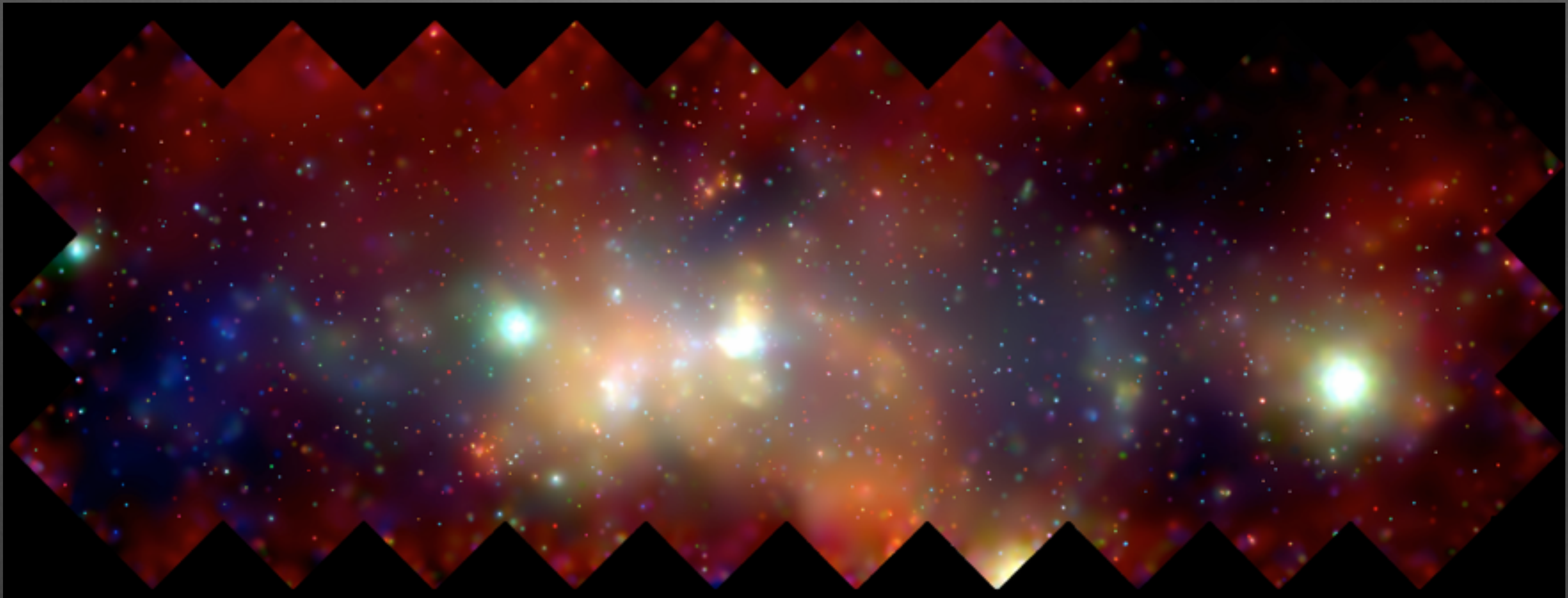
Galactic Diffuse Emission

π^0-decay

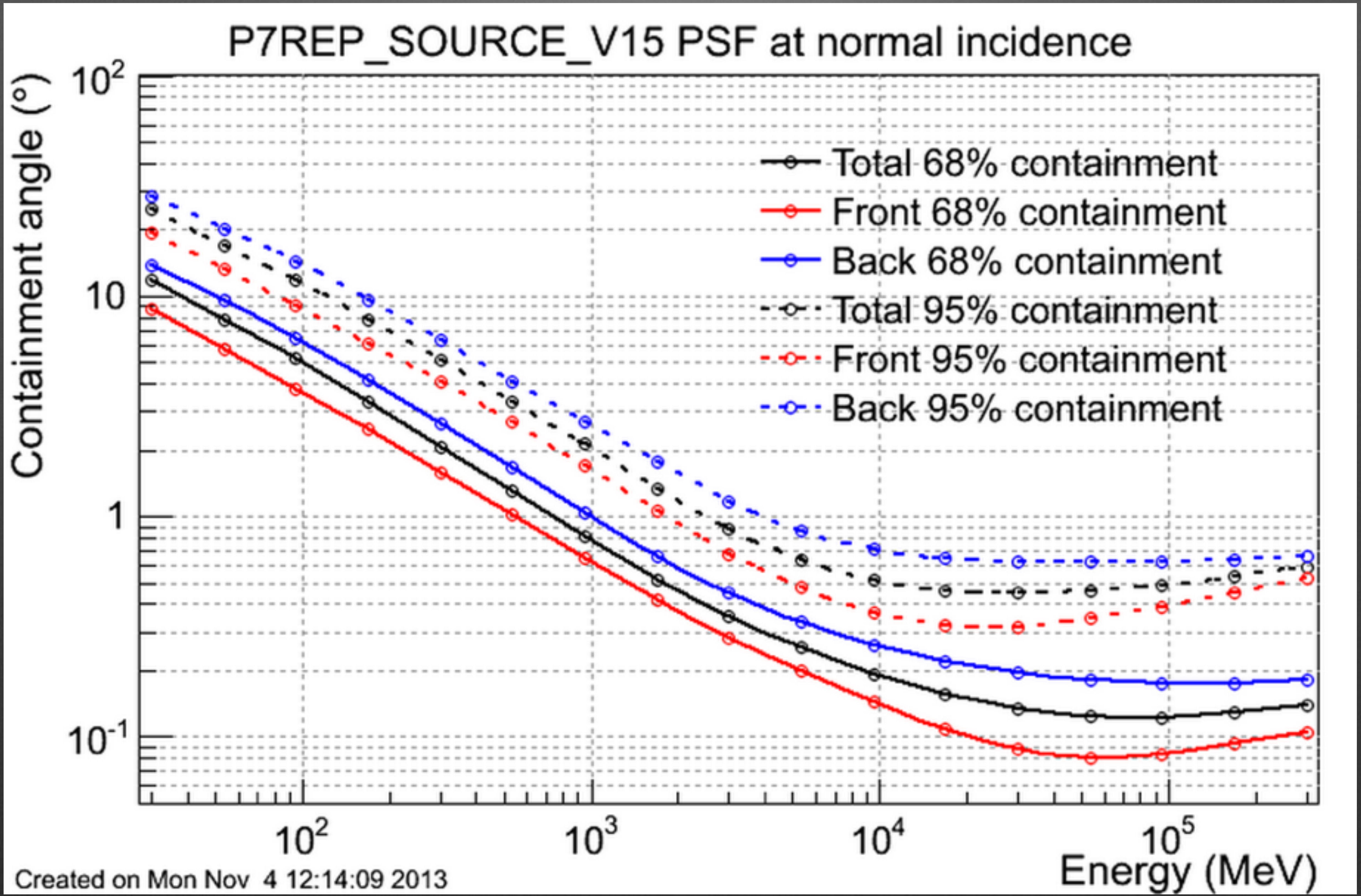
bremsstrahlung

inverse-Compton

The Galactic Center



CTBCORE

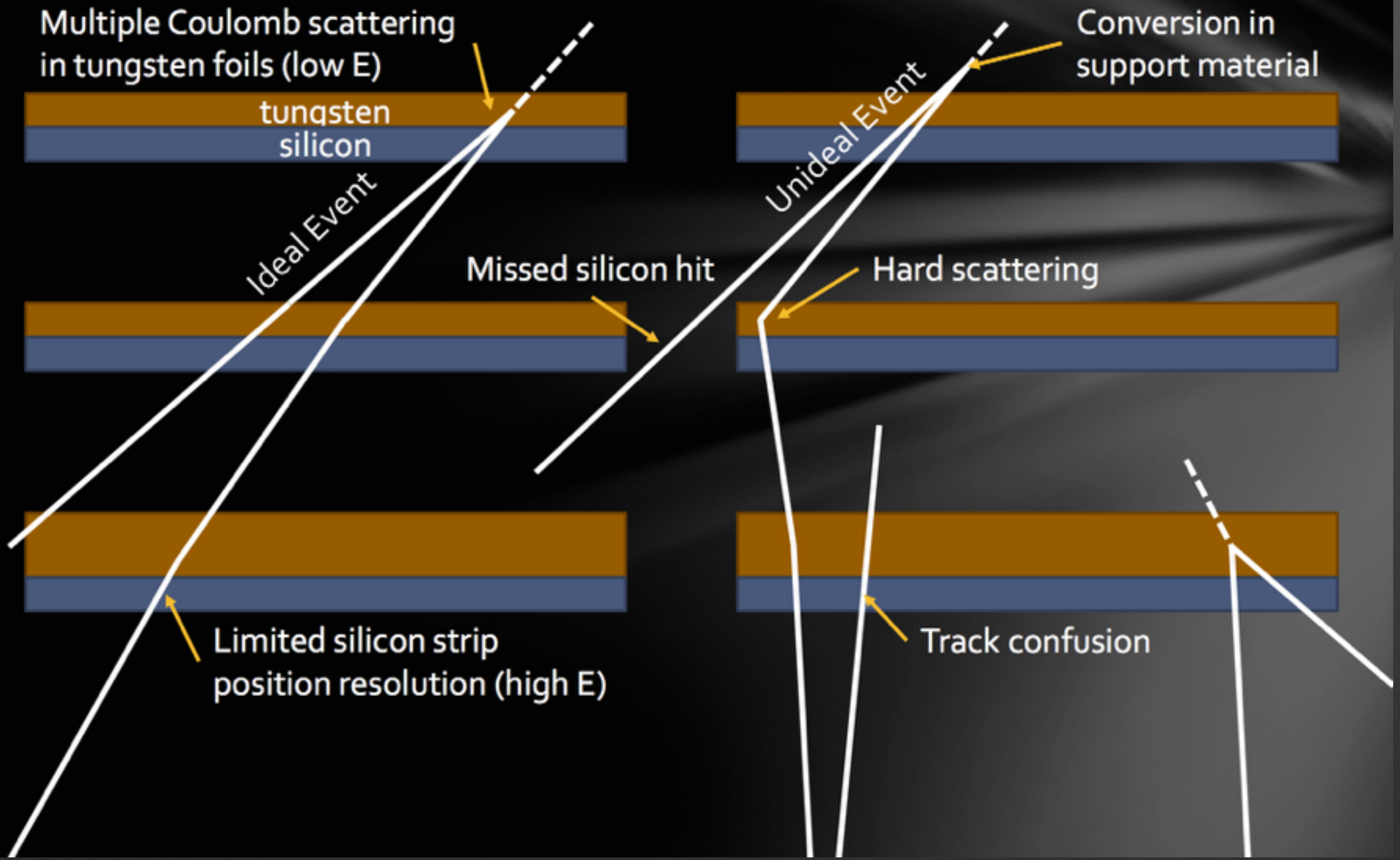


P7REP_SOURCE_V15 PSF at normal incidence
Containment angle (°)
Energy (MeV)
Total 68% containment
Front 68% containment
Back 68% containment
Total 95% containment
Front 95% containment
Back 95% containment
Created on Mon Nov 4 12:14:09 2013

CTBCORE

Slide from Stephen Portillo

Point Spread Function



CTBCORE

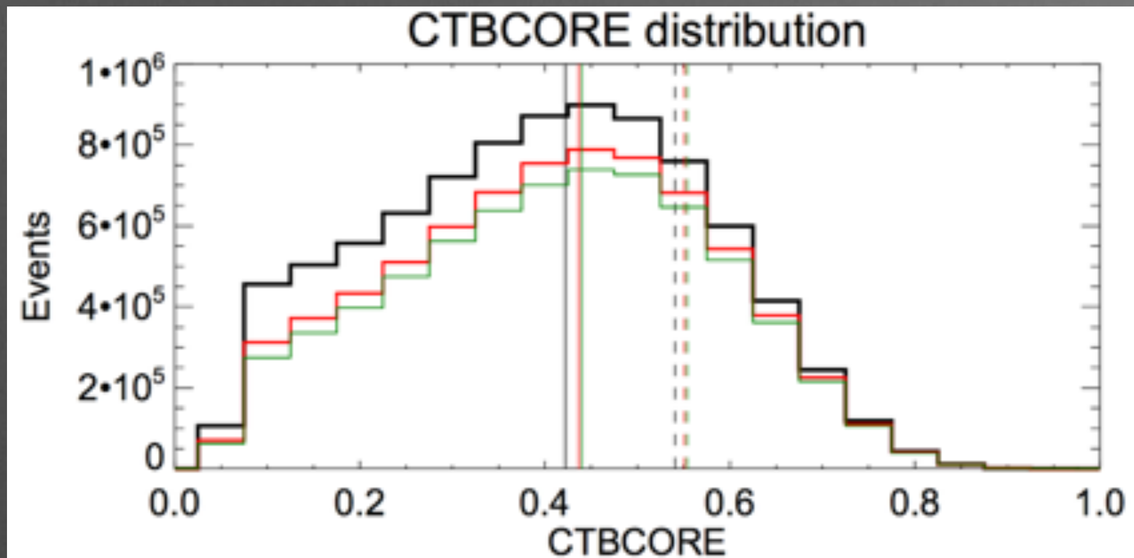
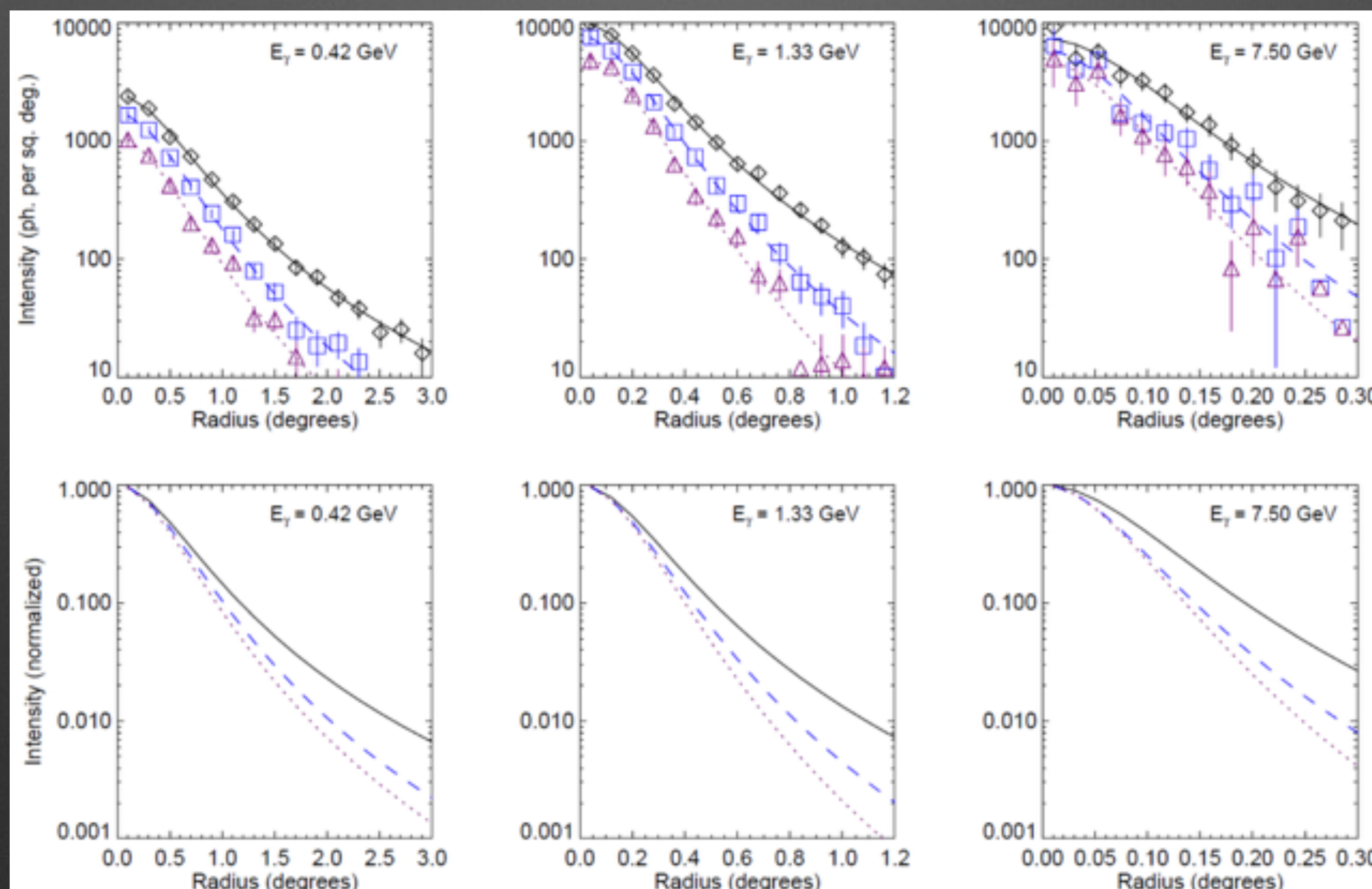


TABLE 3

95% CONTAINMENT RADII DETERMINED FROM THE GEMINGA PULSAR WITH THE ULTRACLEAN ANALYSIS CLASS, AFTER SMOOTHING ENERGY DEPENDENCE

cut	422 MeV	1334 MeV	7499 MeV
no CTBCORE cut	5.0°	2.0°	0.59°
Q2	2.2°	0.91°	0.33°
Q1	1.8°	0.75°	0.24°



Portillo & Finkbeiner (2014)

Two Separate Analyses

Inner Galaxy

- $|b| > 1^{o}$
- Bright point sources masked at 2^{o}
- Allow diffuse templates (galactic diffuse, isotropic, Fermi bubbles, dark matter) to float independently in each of 30 energy bins

Galactic Center

- $|b| < 5^{o}$, $|l| < 5^{o}$
- Include and model all point sources (37 d.o.f.)
- Use likelihood analysis to calculate the spectrum and intensity of each source component
- Calculate log-likelihood to determine significance of component

Two Separate Analyses

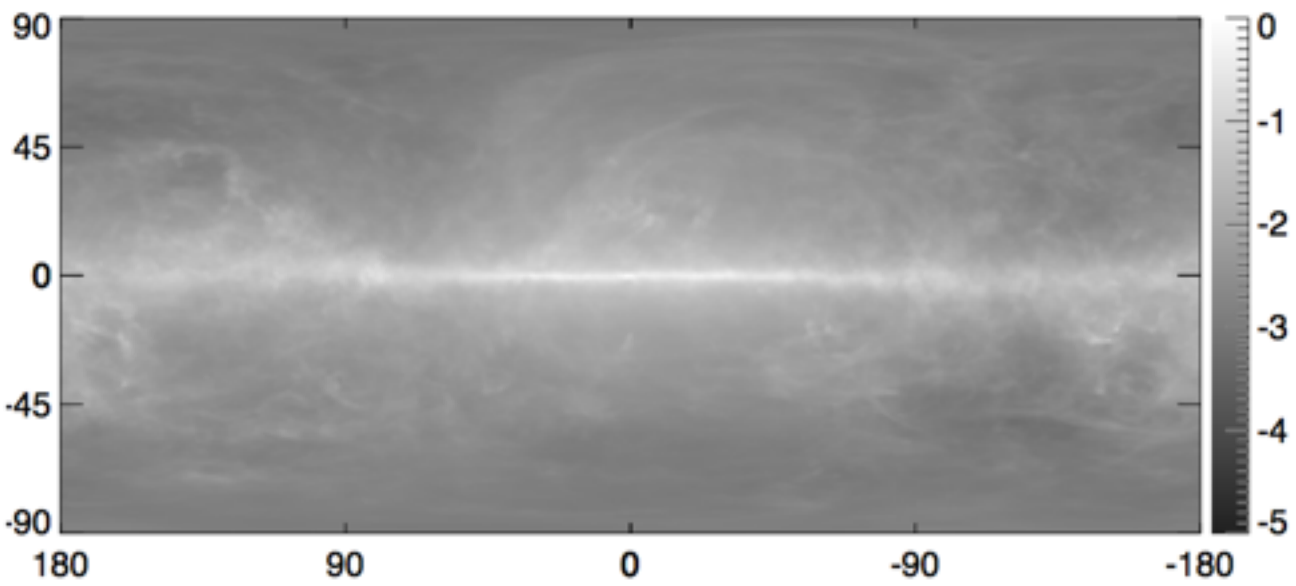
Inner Galaxy

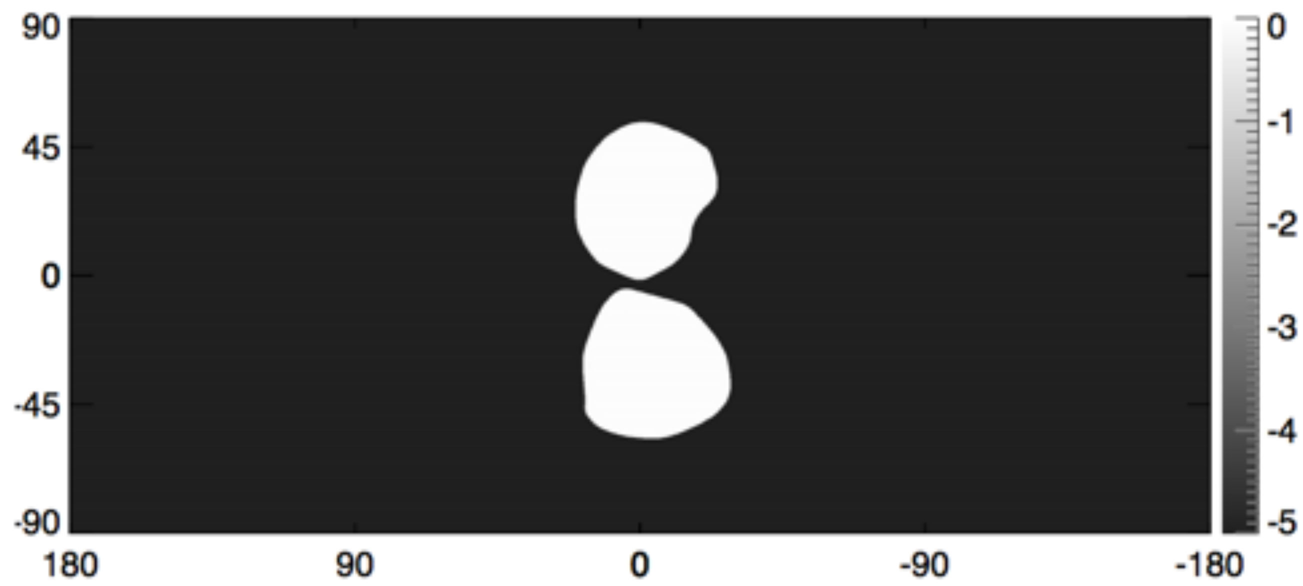
- **Advantages:**
  - Less astrophysical contamination
  - Fewer parameters in fit
  - Instrumental PSF Doesn't Matter
- **Disadvantages:**
  - Signal is dimmer
  - Can't test center profile
  - Fit parameters may be skewed by the entire sky

Galactic Center

- **Advantages:**
  - Signal brighter
  - Can test profile in inner regions
- **Disadvantages:**
  - More astrophysical contamination
  - Many free parameters
  - Bin by bin energy analysis is impossible

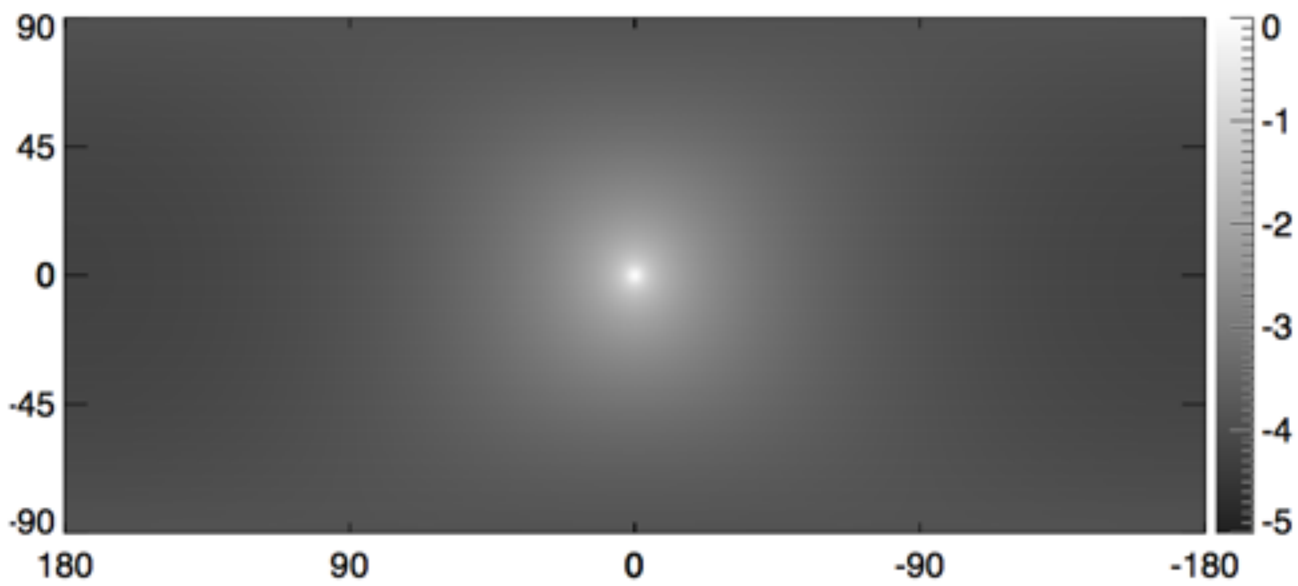
Dark Matter Template





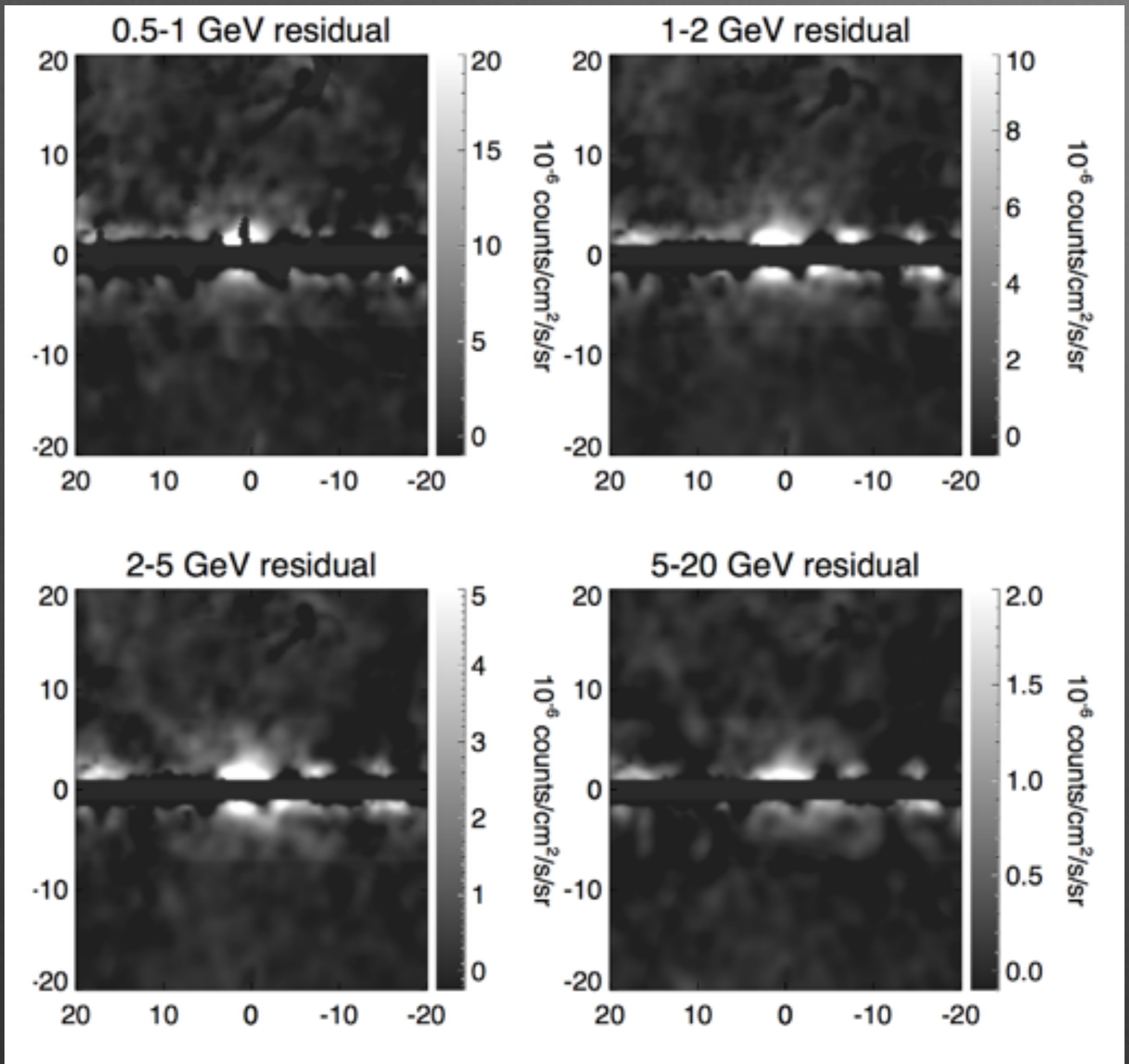
Diffuse

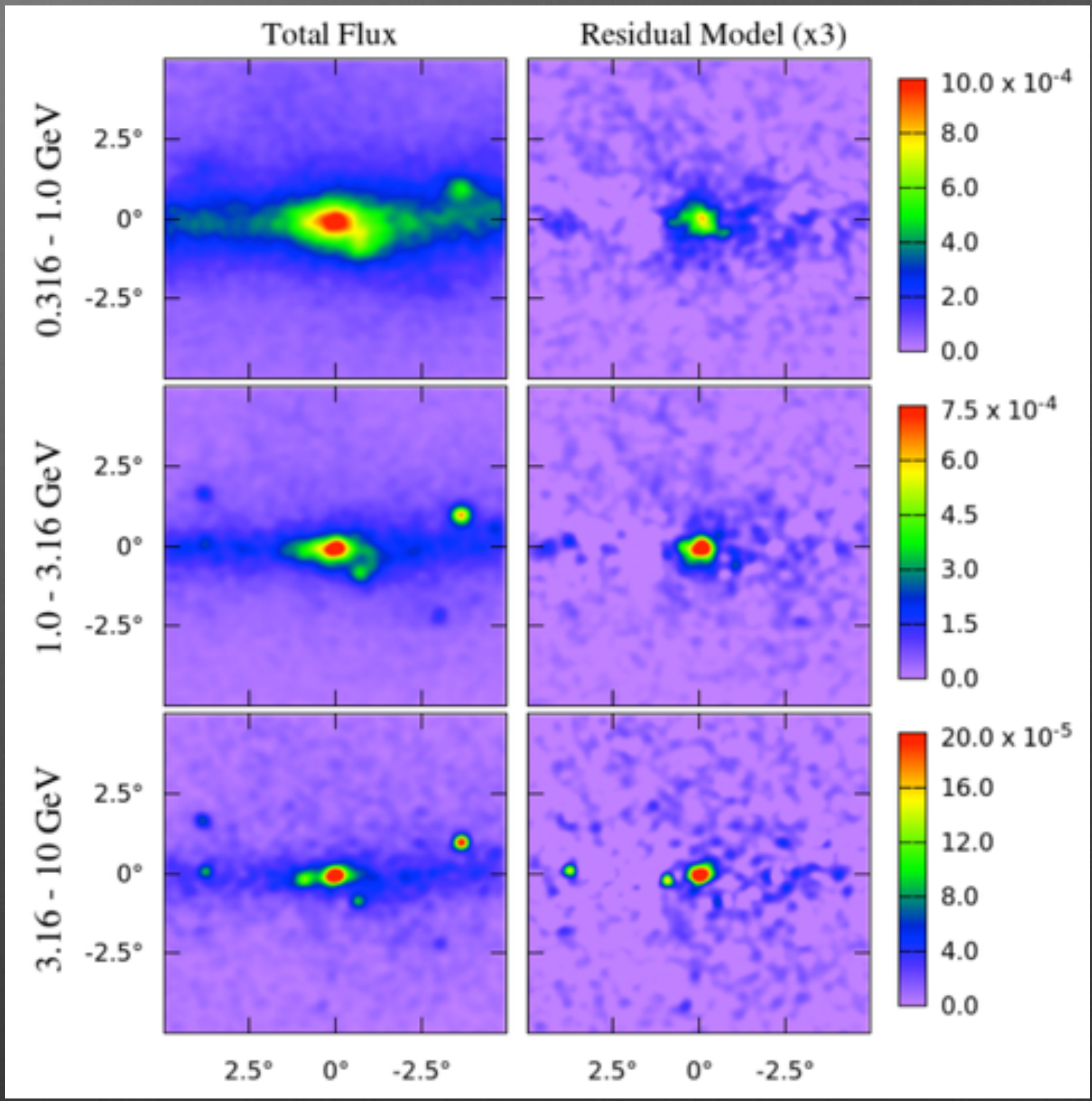
Bubbles



DM

Consistent Results!

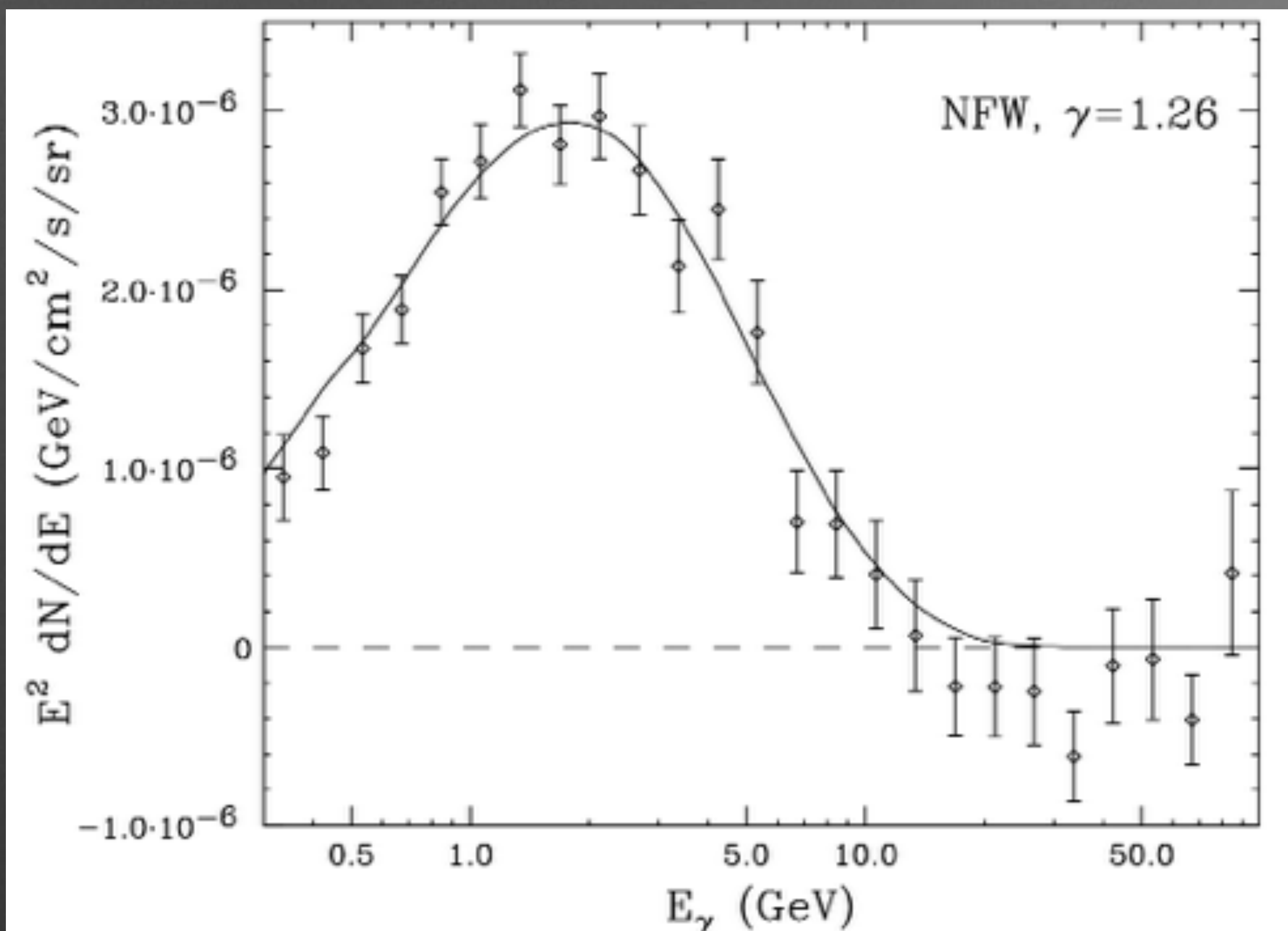




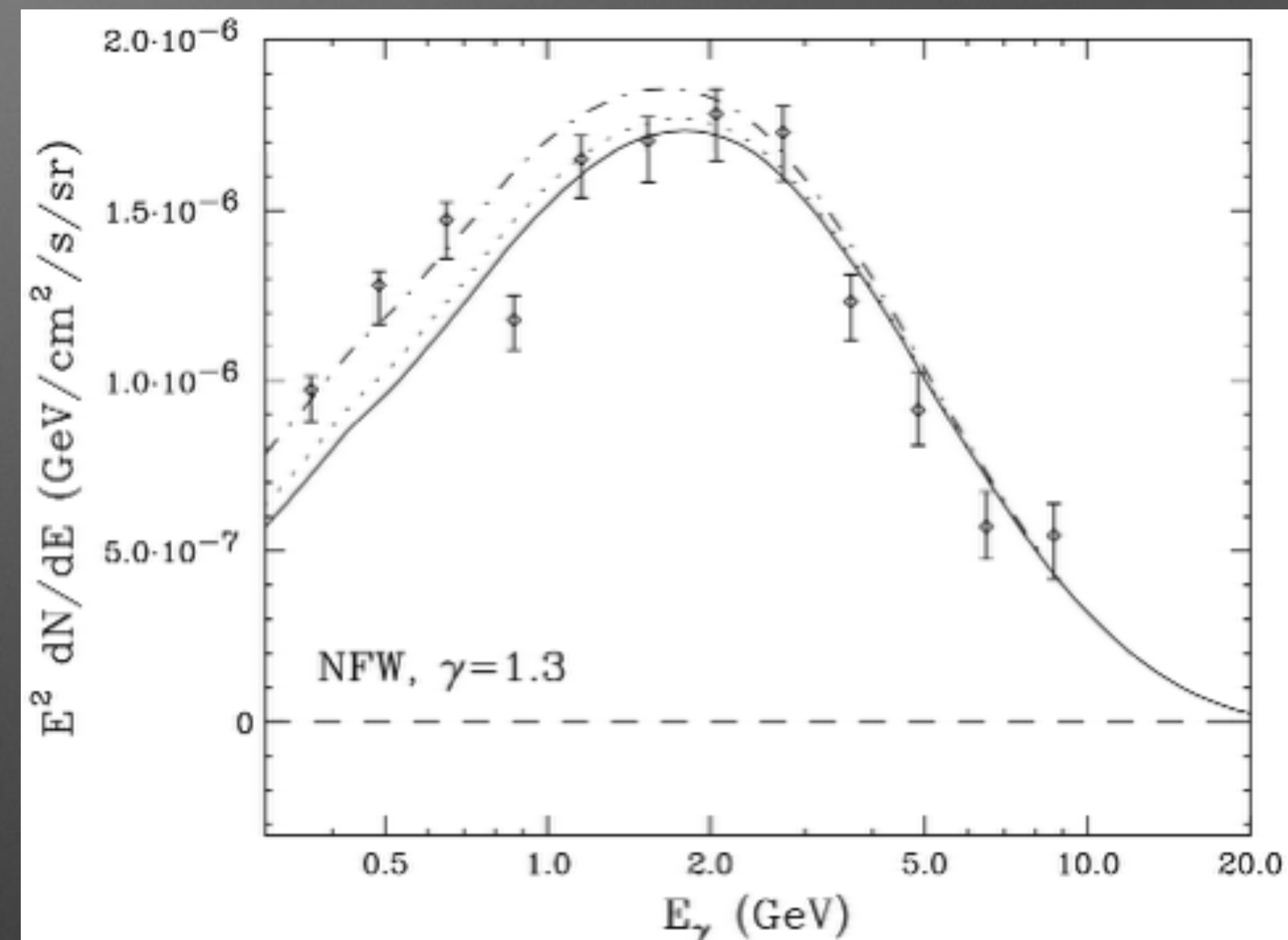
Inner Galaxy

Galactic Center

Consistent Results!

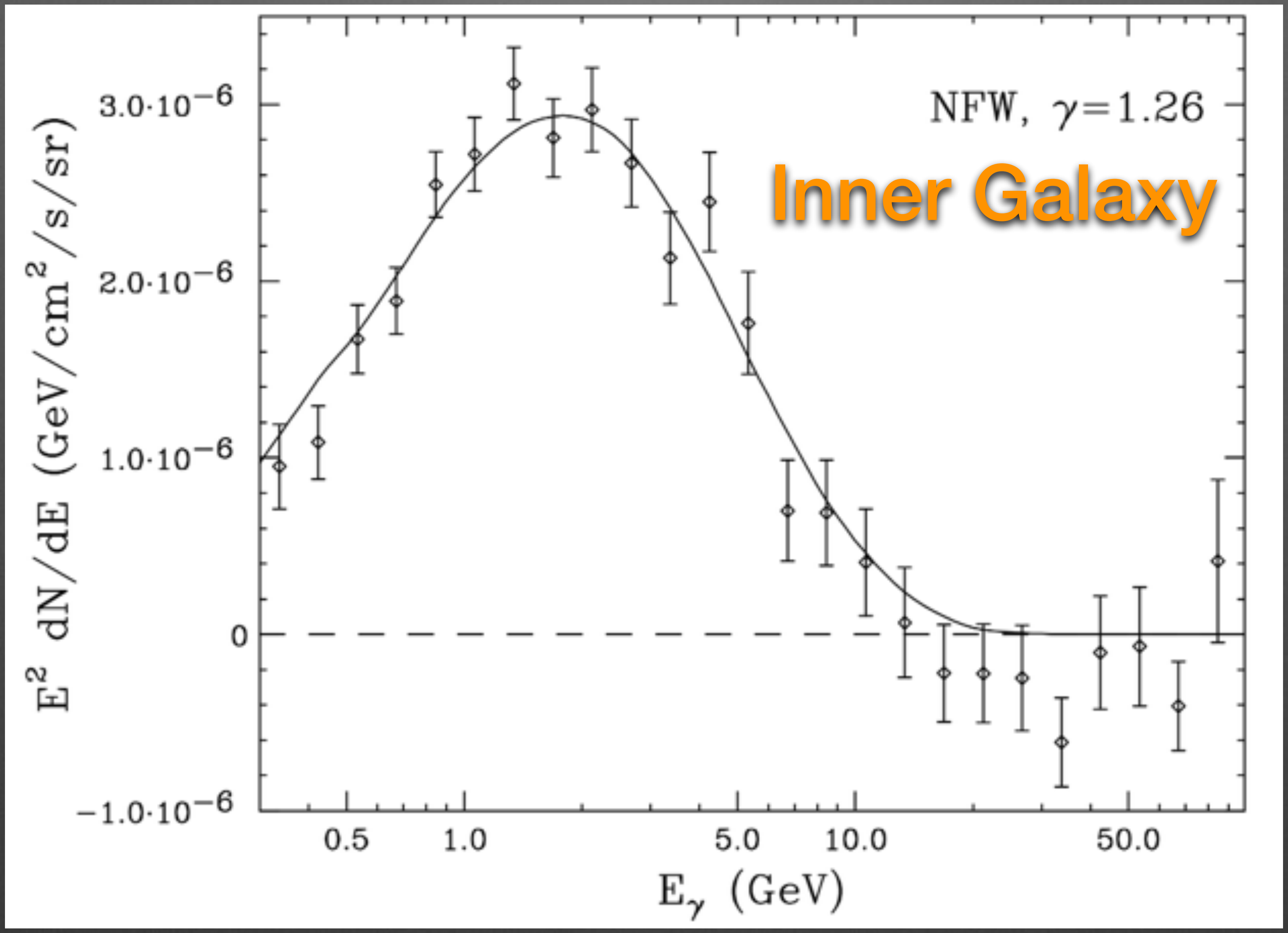


Inner Galaxy



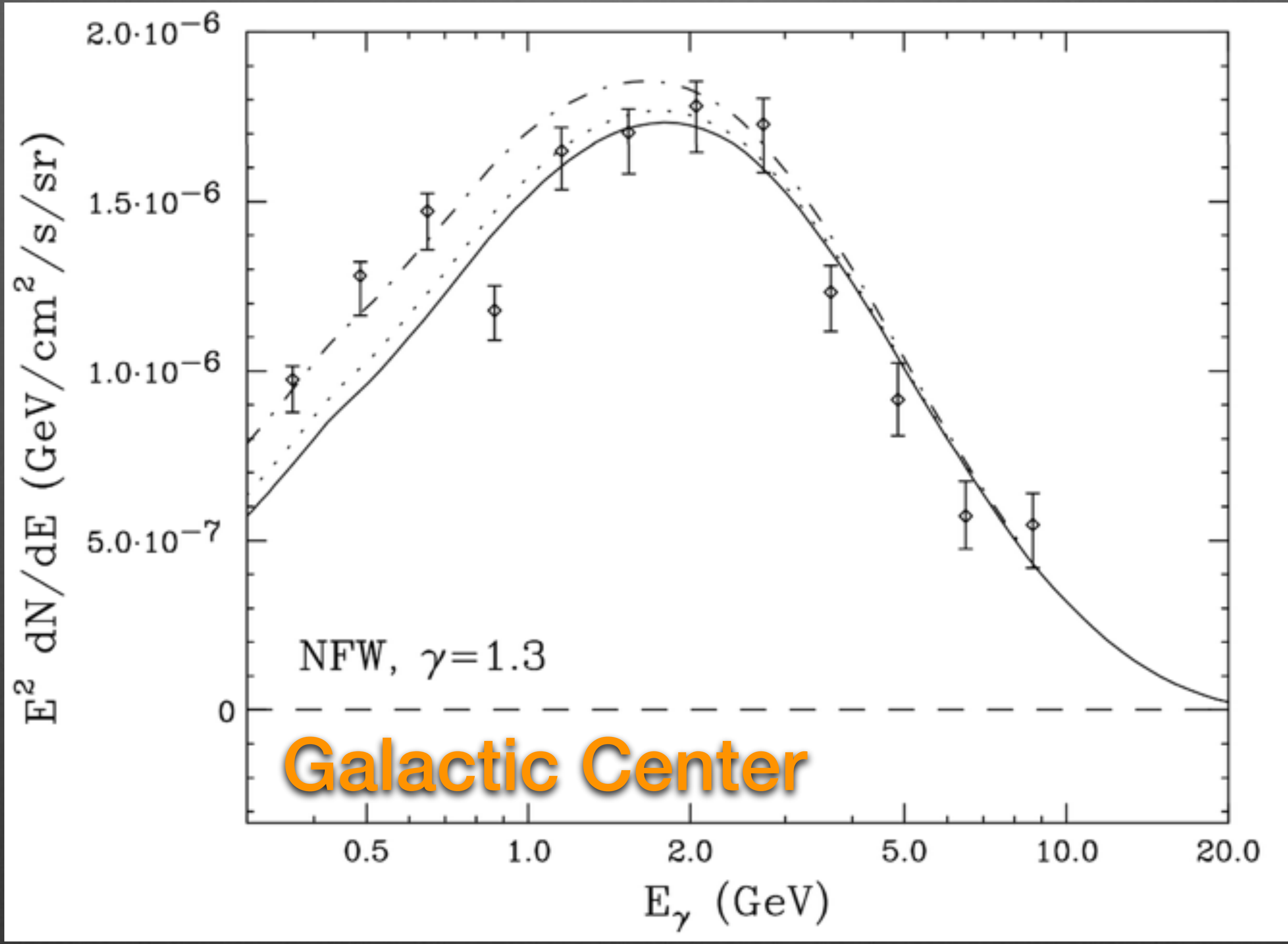
Galactic Center

Inner Galaxy



Note that this spectrum is calculated independently in *each* energy bin. Thus we are relatively immune to spectral uncertainties in the diffuse model or other astrophysical backgrounds.

Galactic Center



This spectrum is computed as an iterative process as follows:

Iterative Procedure

This spectrum is computed as an iterative process as follows:

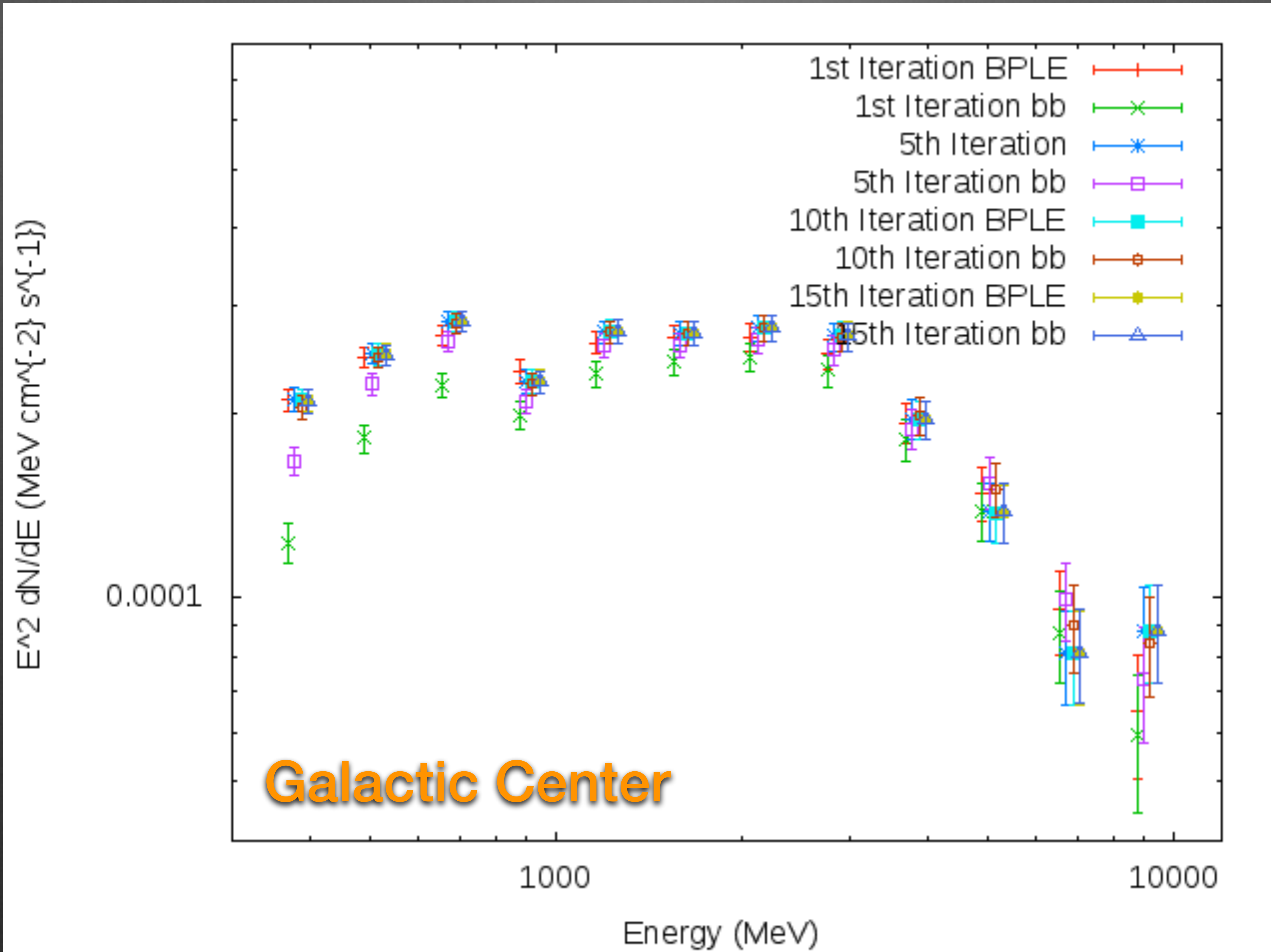
1.) Make an input spectrum for the spherically symmetric component (used 8 GeV -> $\tau^+\tau^-$, 30 GeV -> bb, Broken Power Law with an Exponential Cutoff)

2.) Calculate the fit

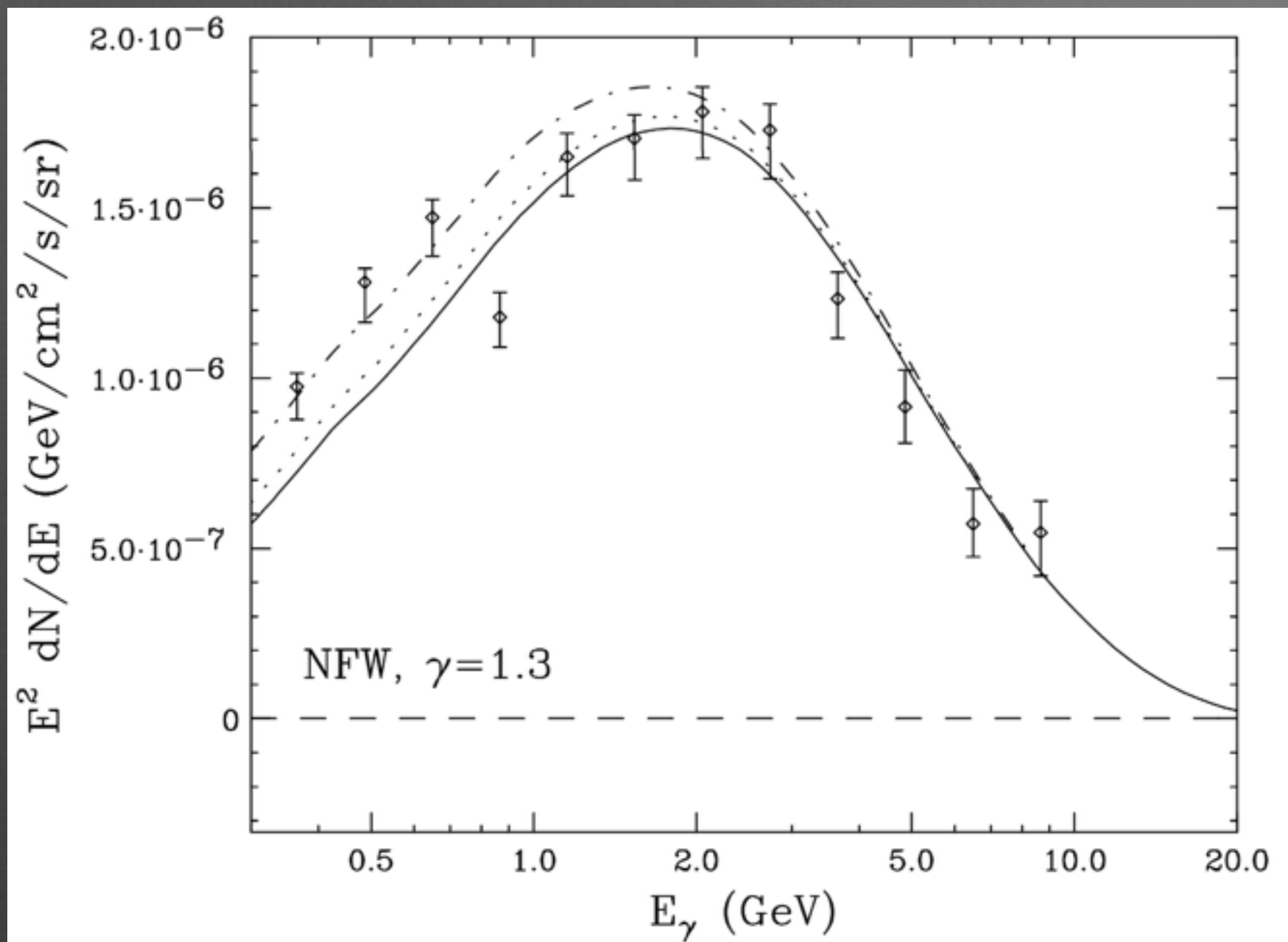
3.) Let the spherically symmetric template fit to a better normalization in each energy bin, to soak up the residual

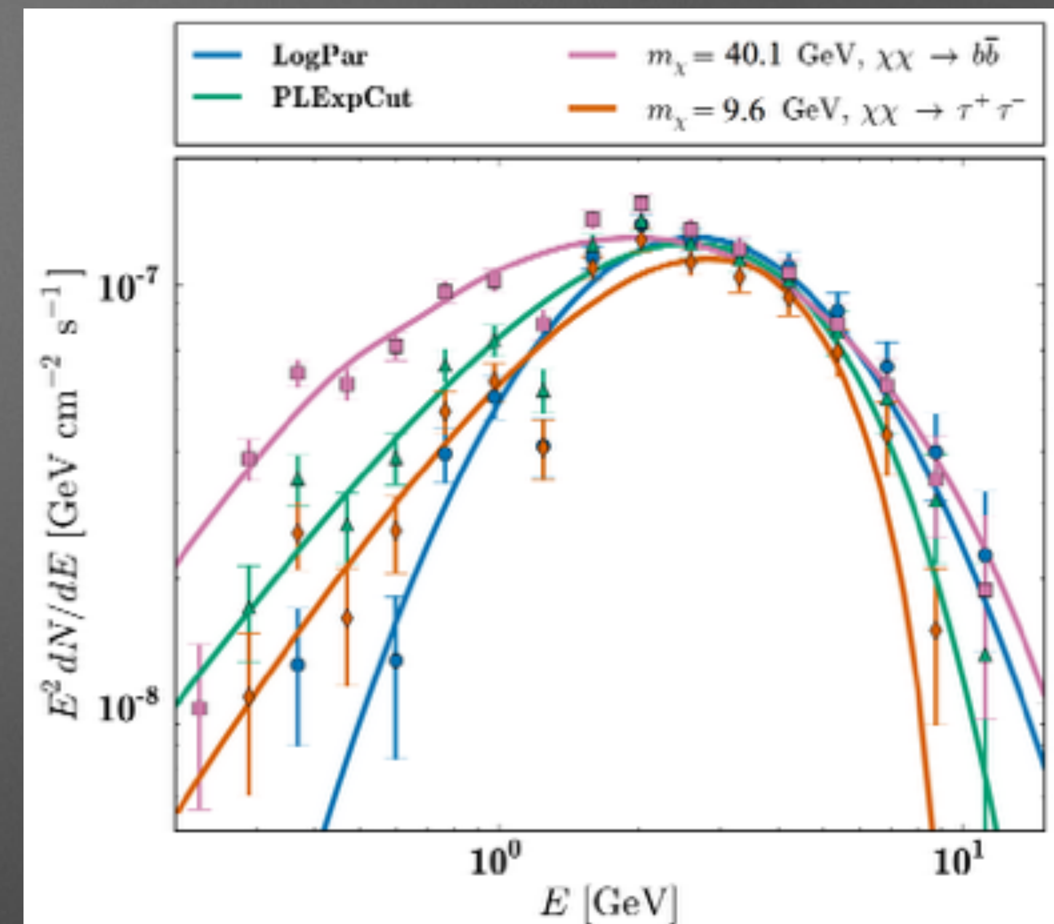
4.) Use this as an input spectrum and refit

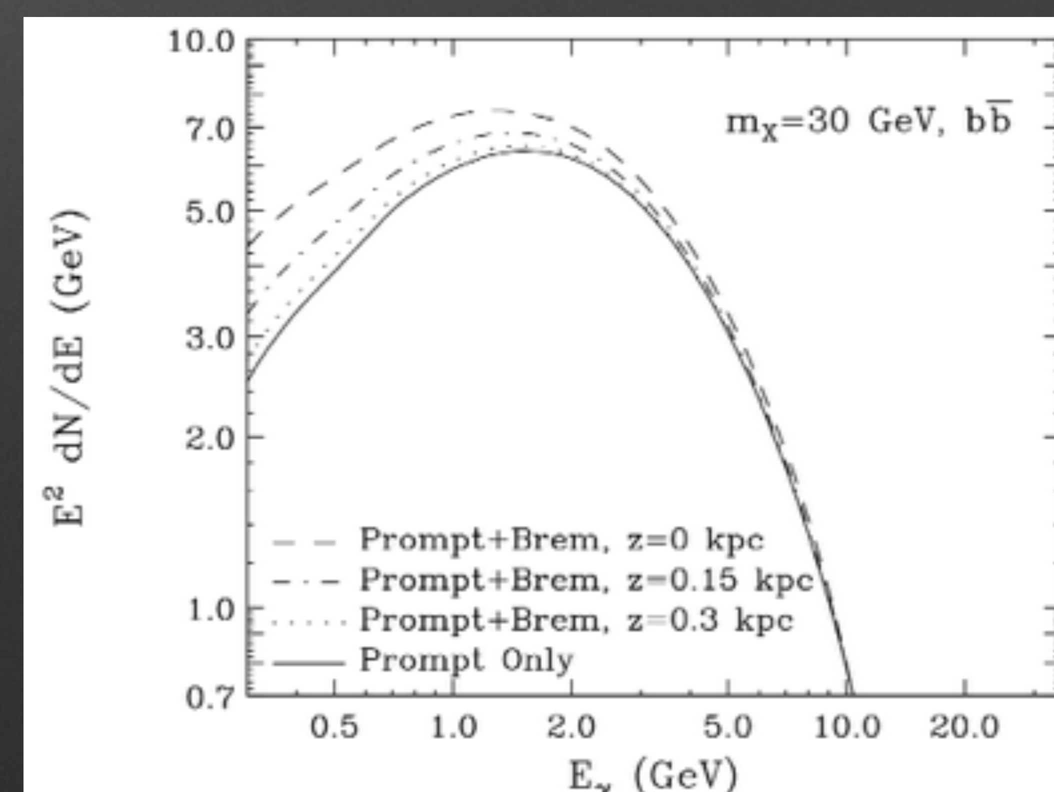
Iterative Procedure Converges



Iterative Procedure Converges





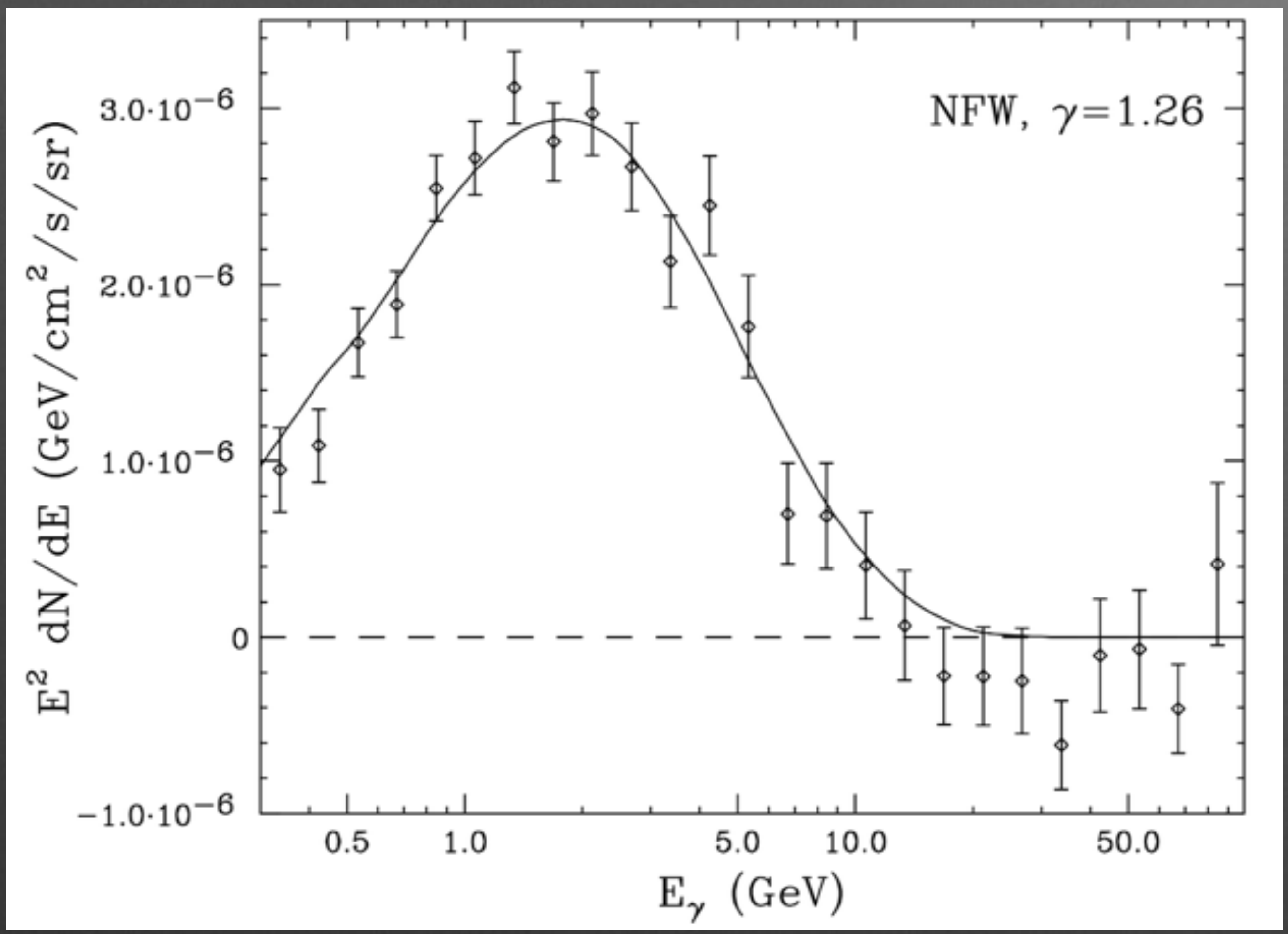


Measurement - The poor PSF of the Fermi-LAT at low energies makes it difficult to distinguish between diffuse emission and point sources

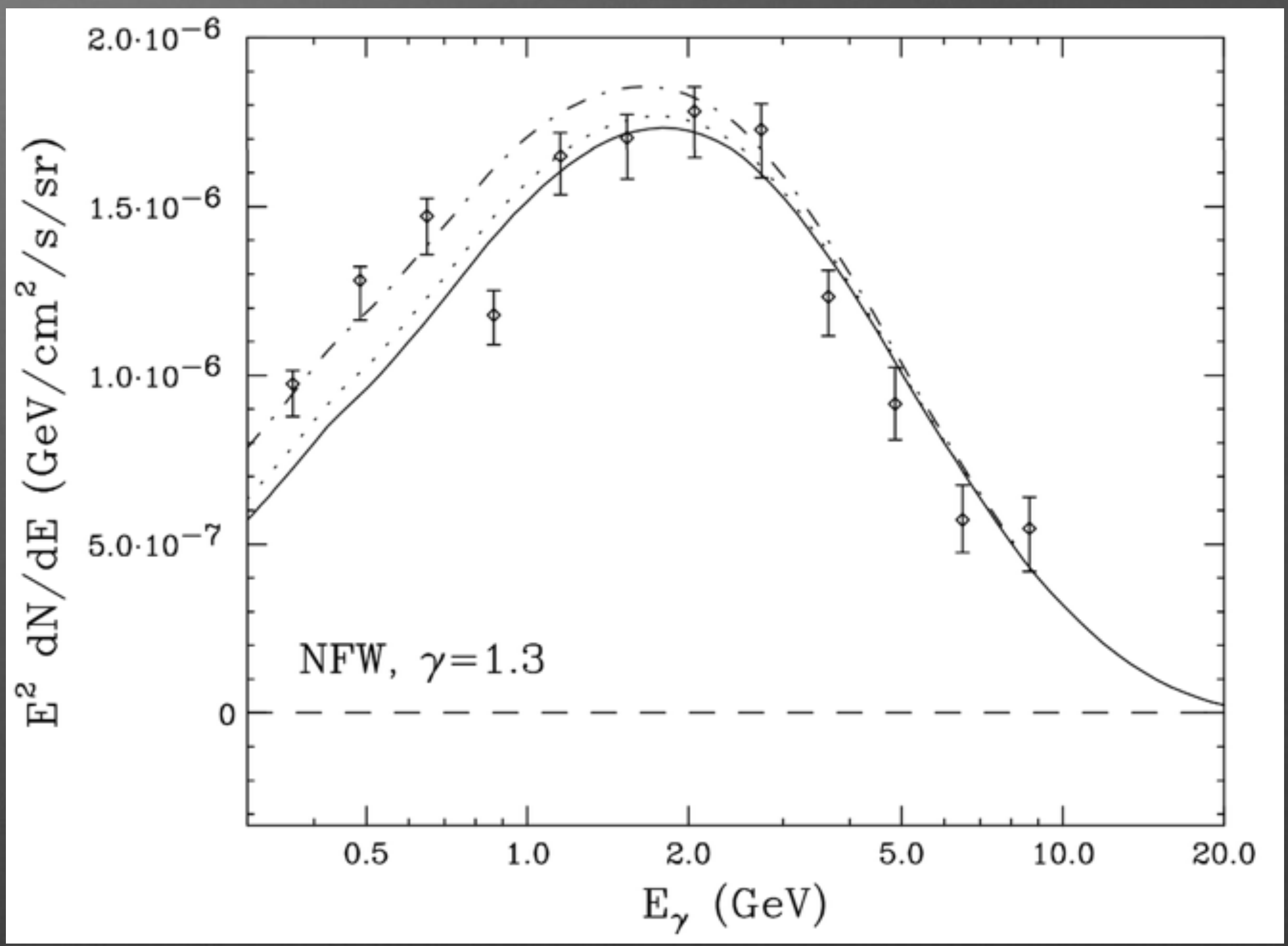
Theory - Any dark matter annihilation will also produce e^+e^- pairs and bremsstrahlung

Galactic Center

Consistent Results!

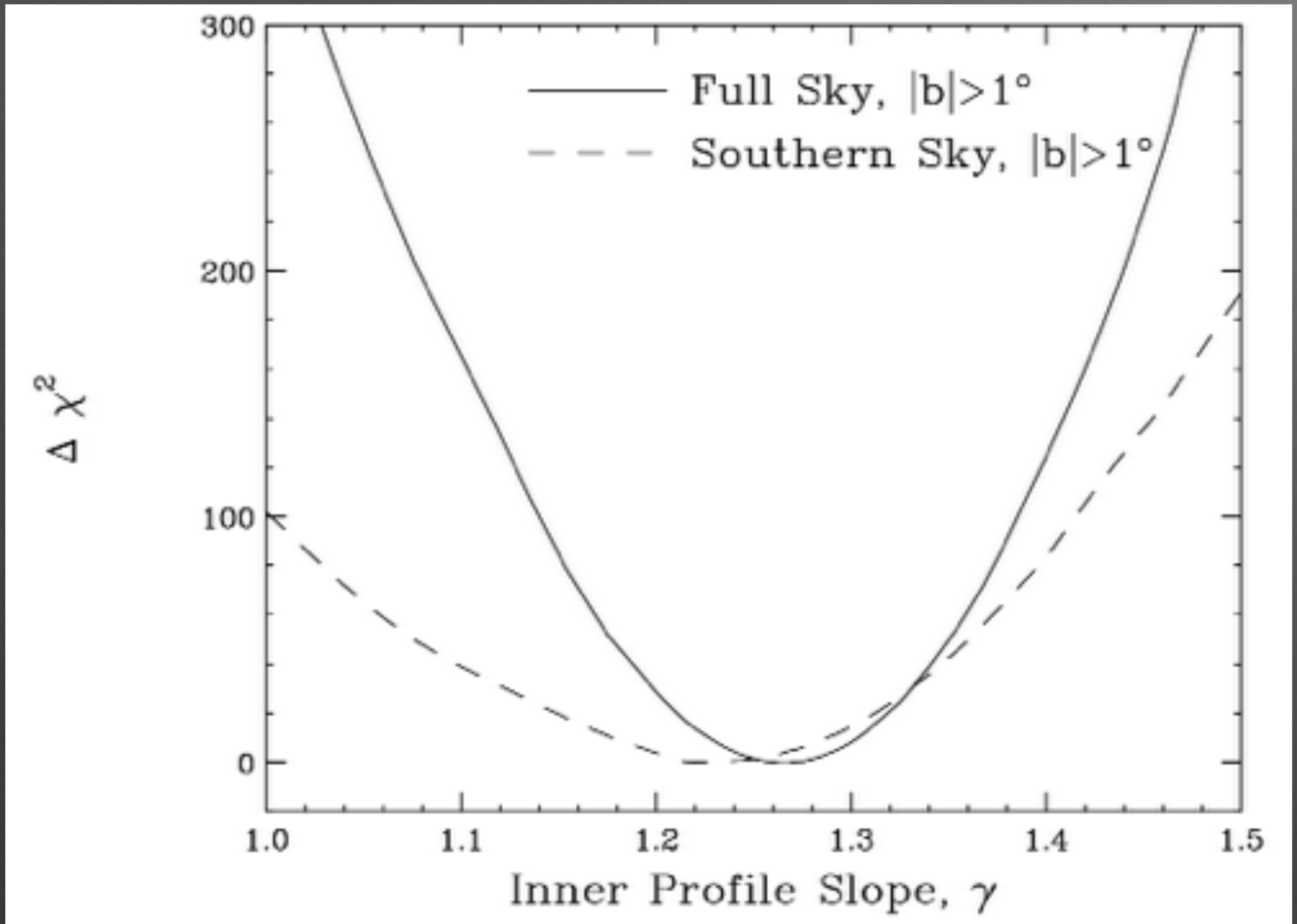


Inner Galaxy

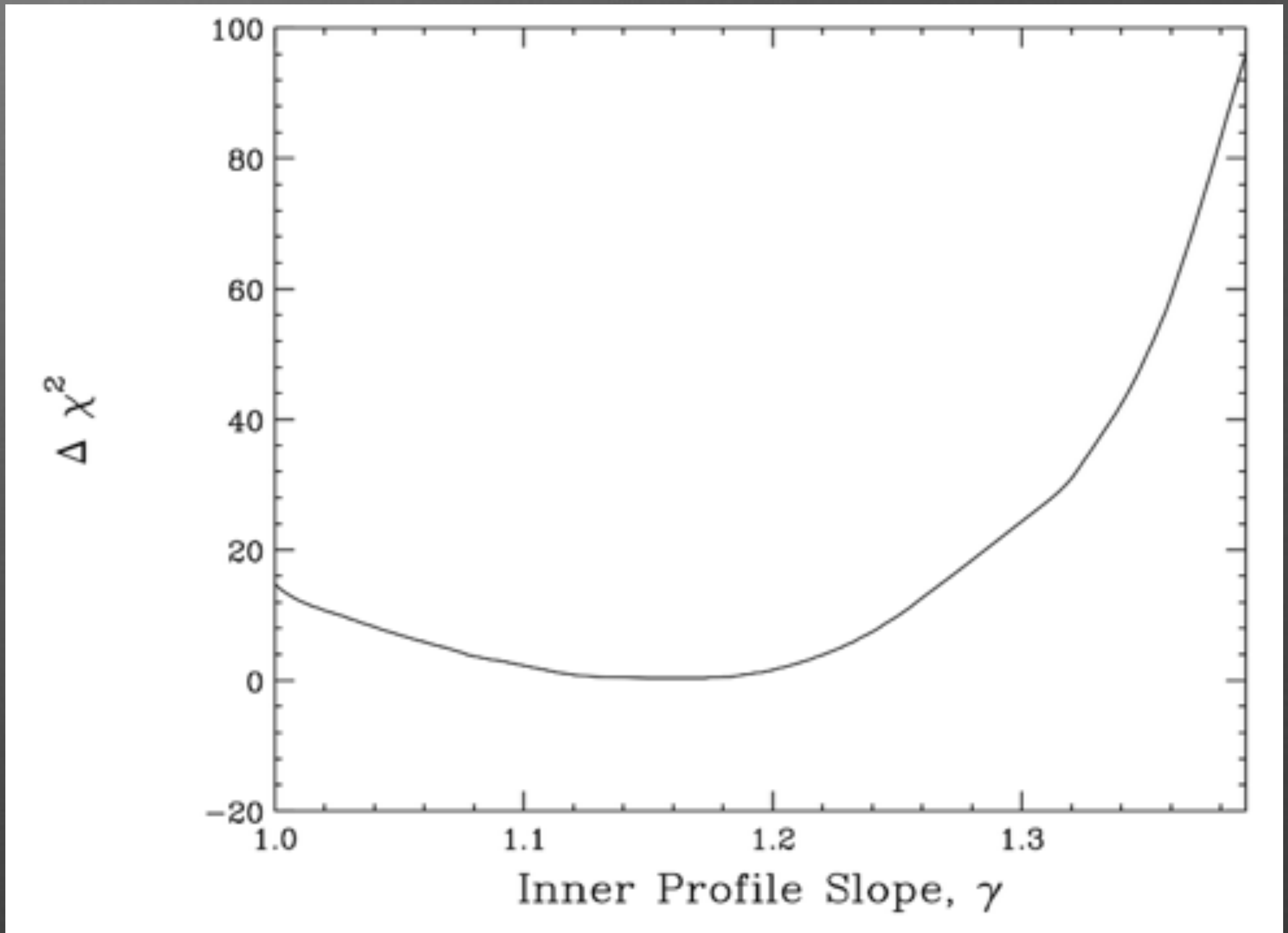


Galactic Center

Consistent Results!

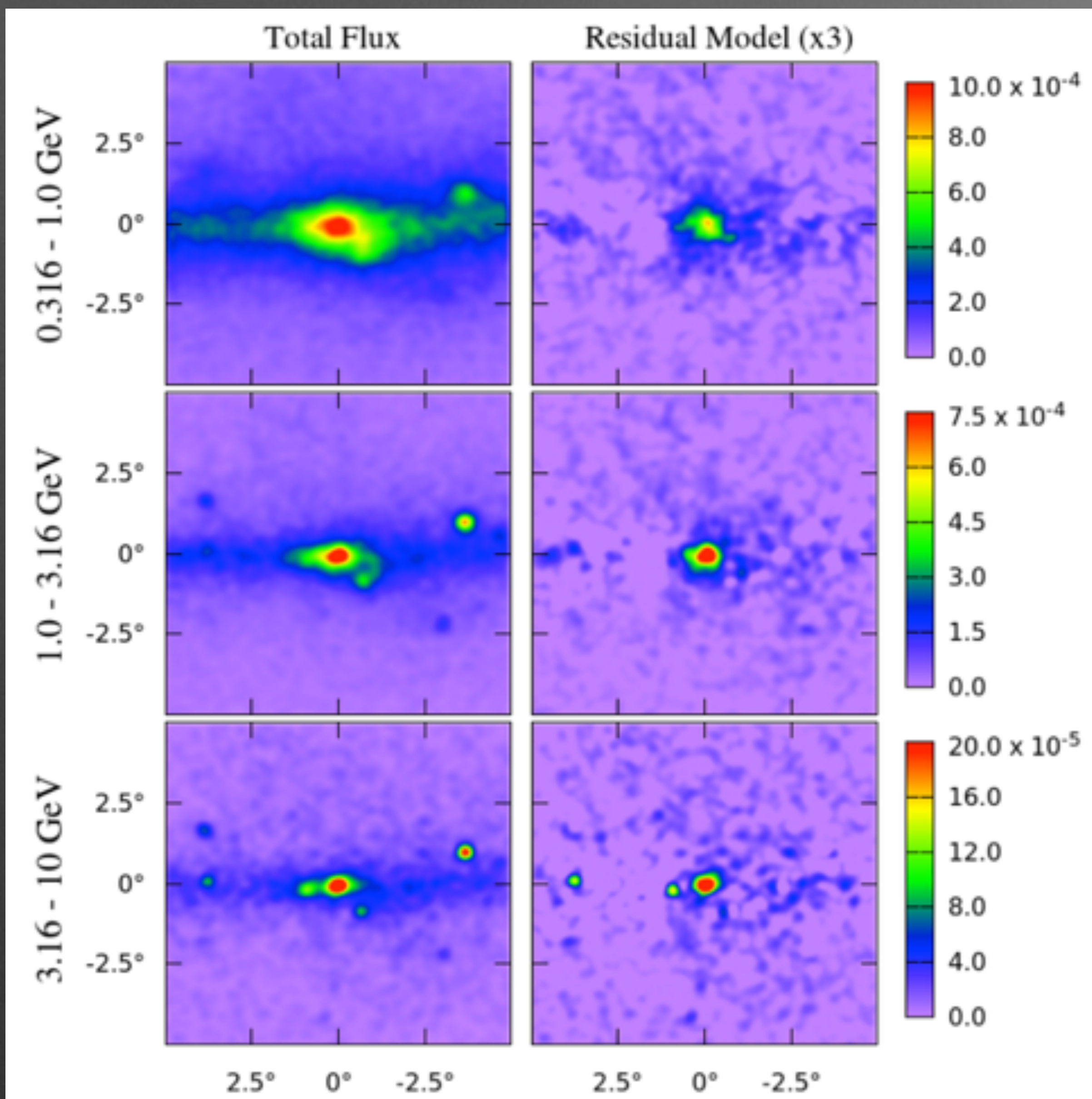


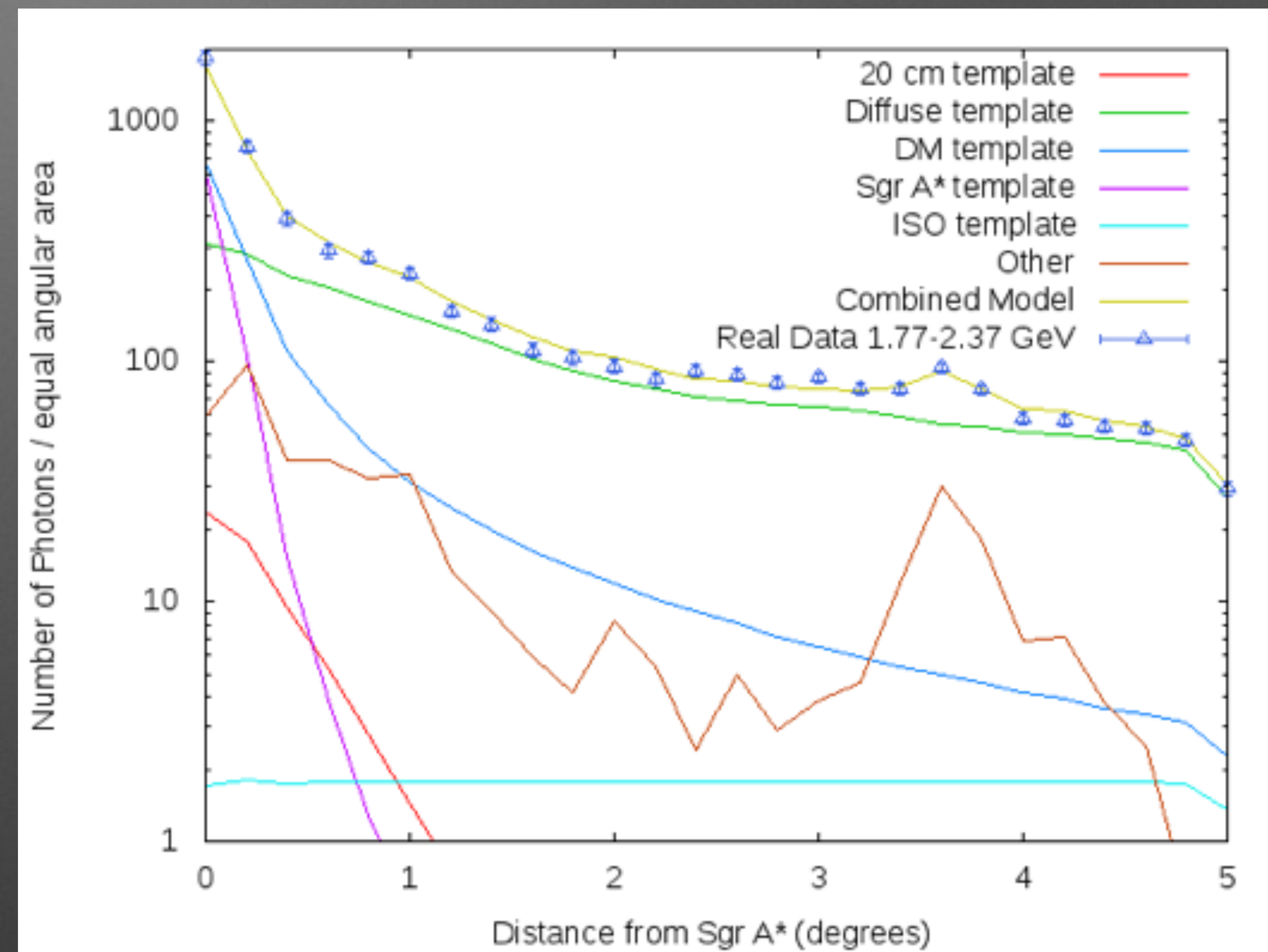
Inner Galaxy



Galactic Center

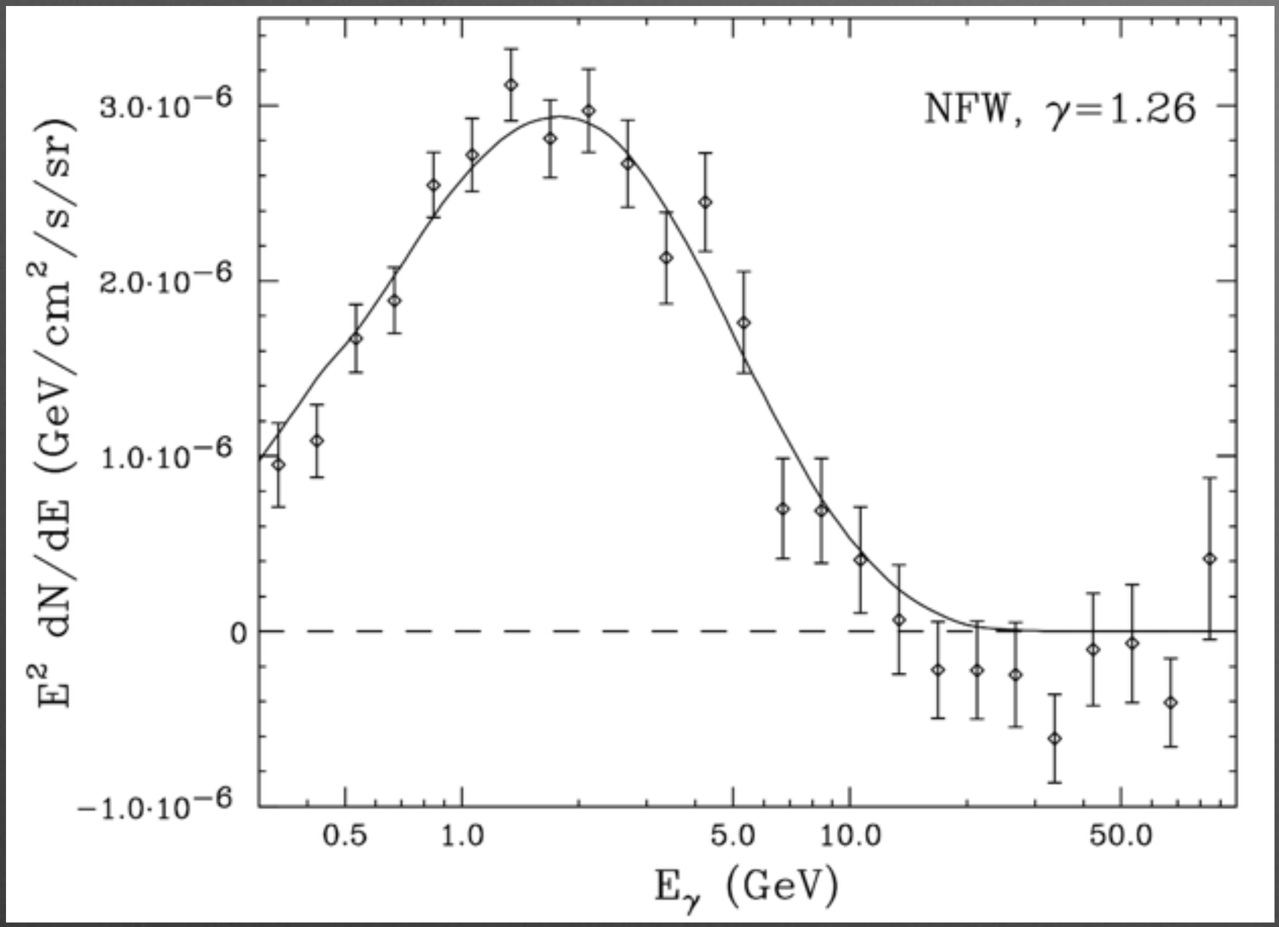
The Magnitude of the Signal

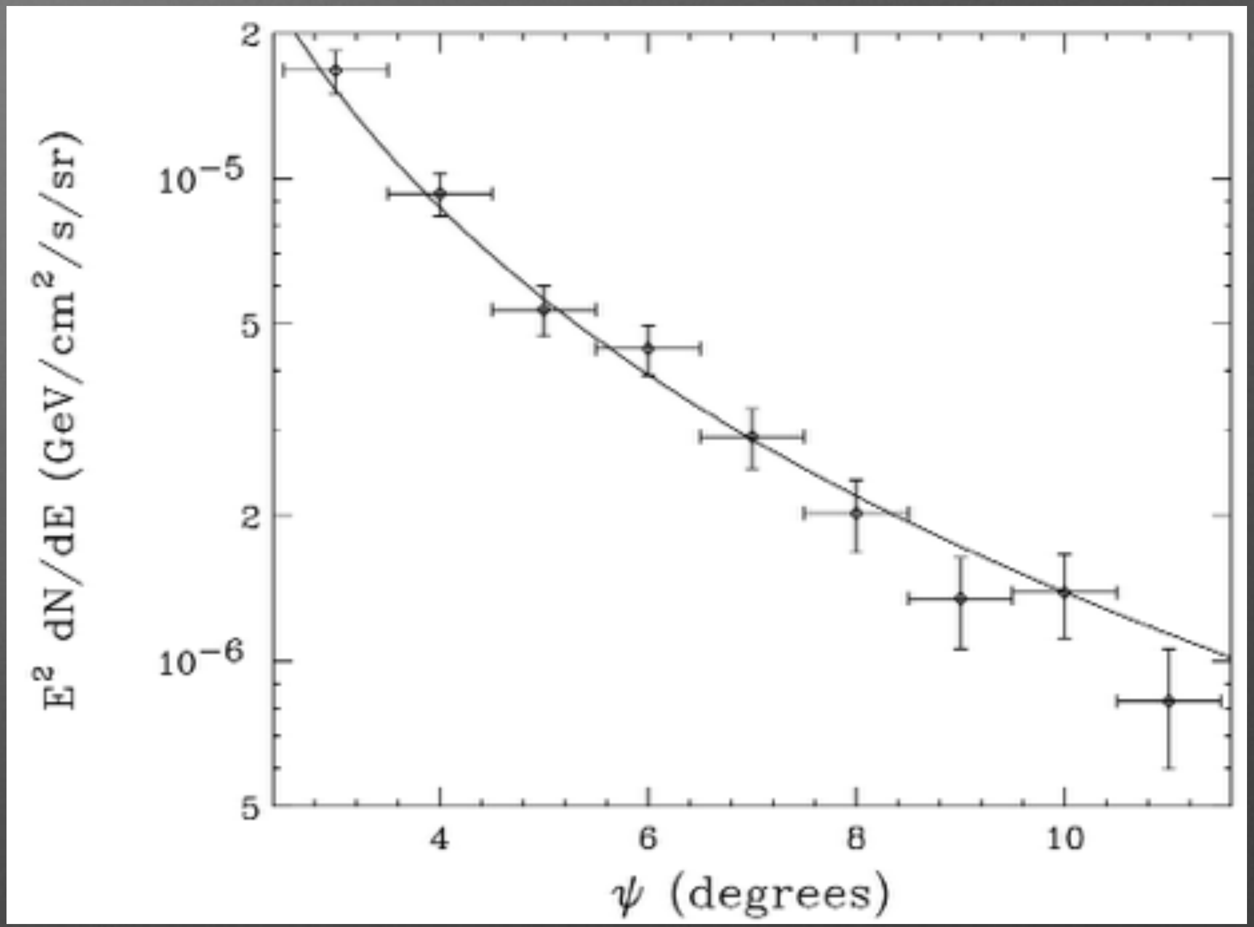


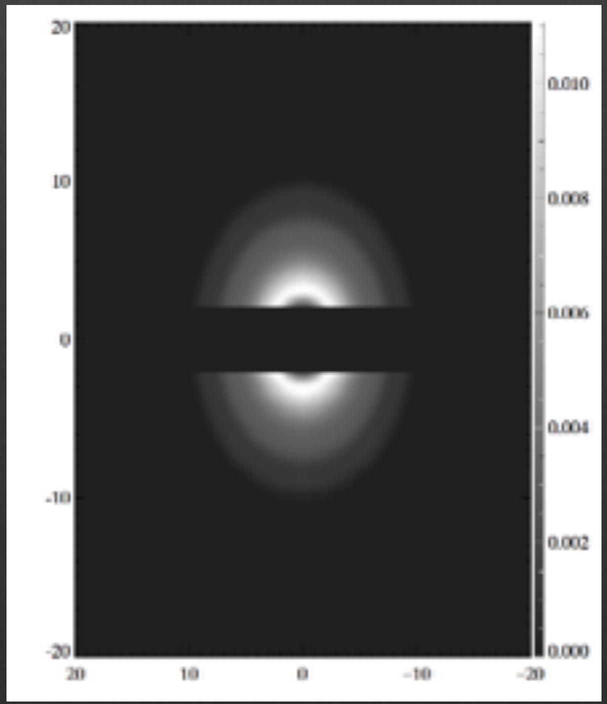


Galactic Center

Spectral vs. Morphological Fitting: The Ring Fit Analysis

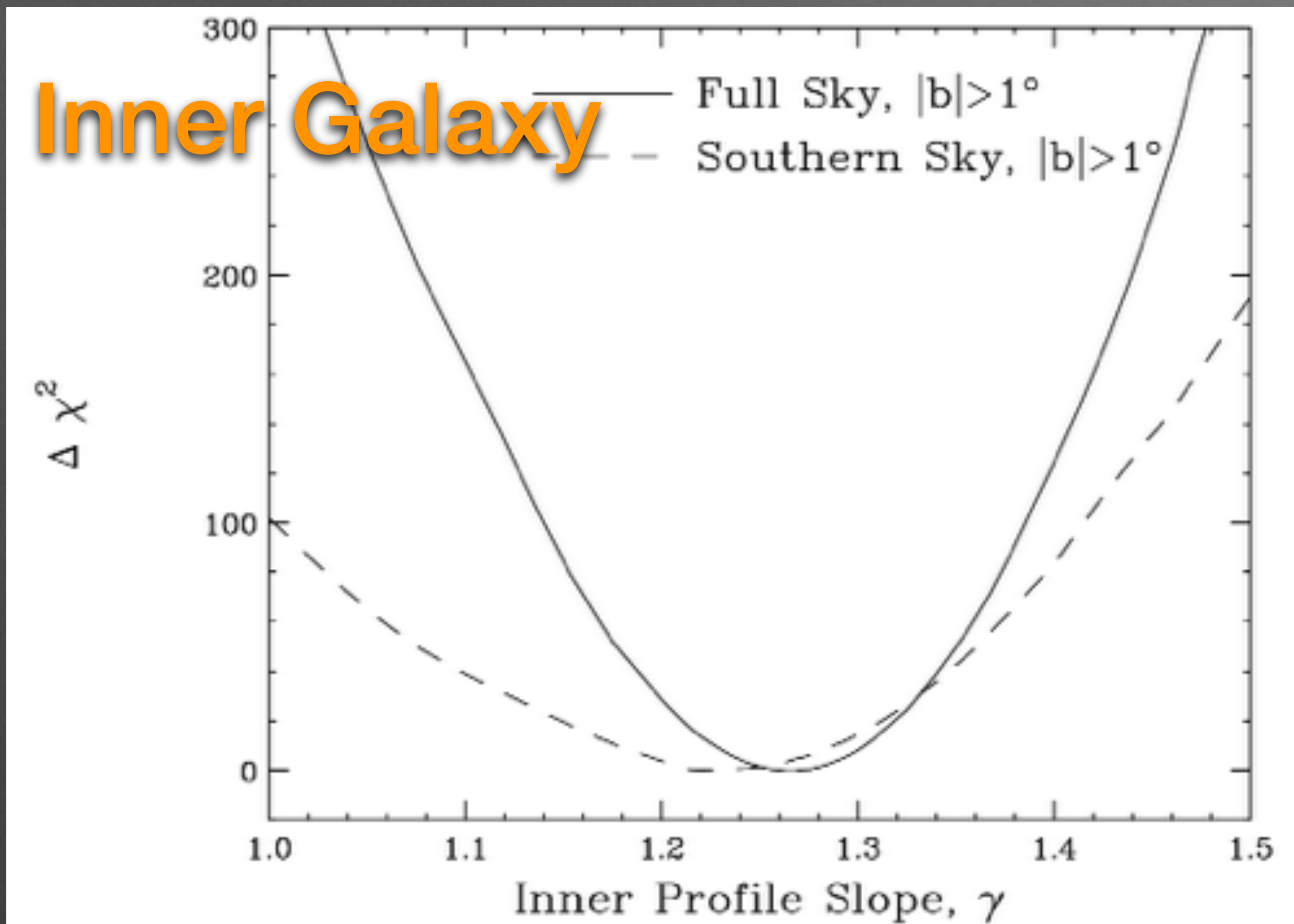


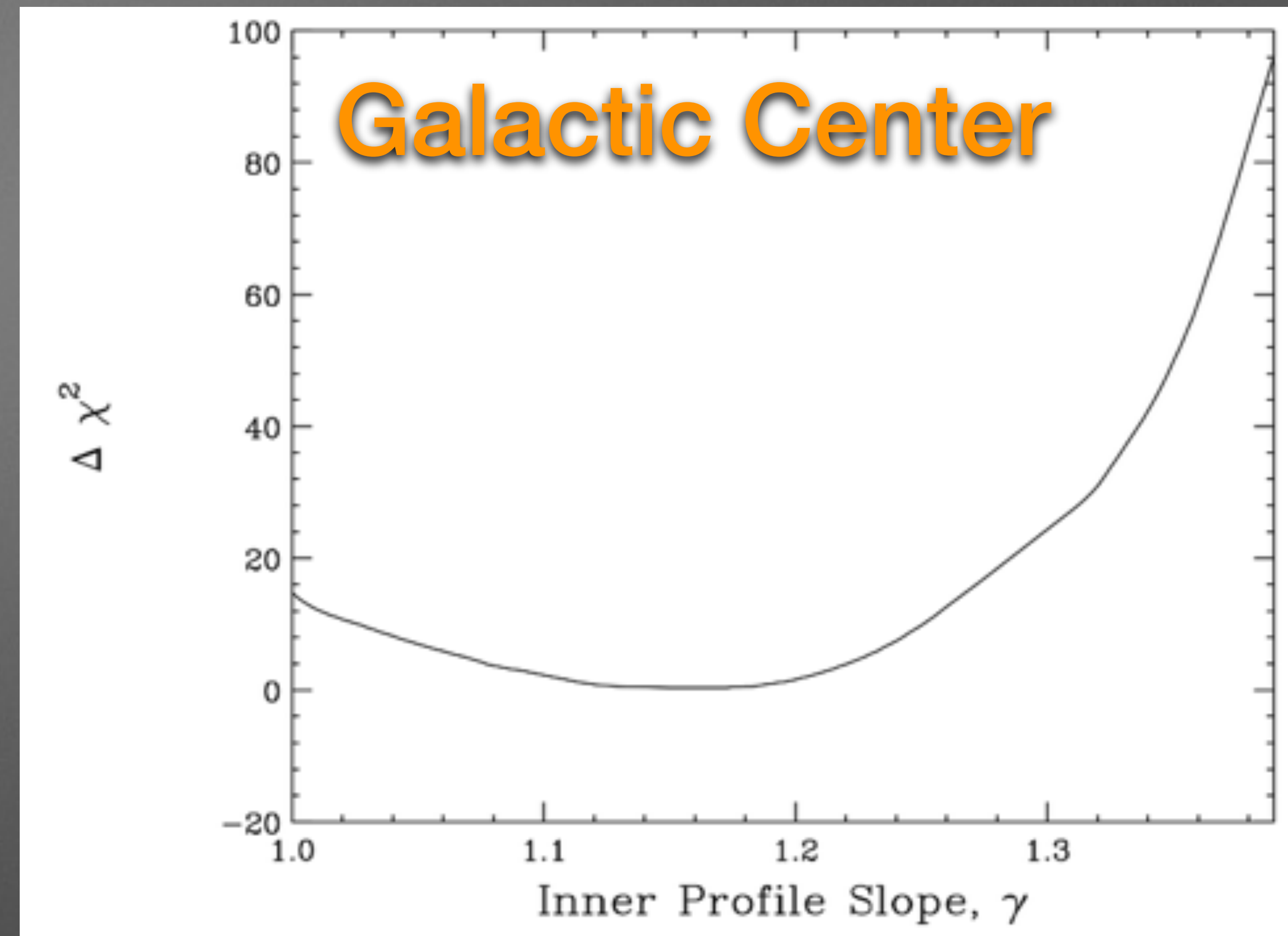




Inner Galaxy

Some (Very Slight) Evidence for Changes in the Profile?





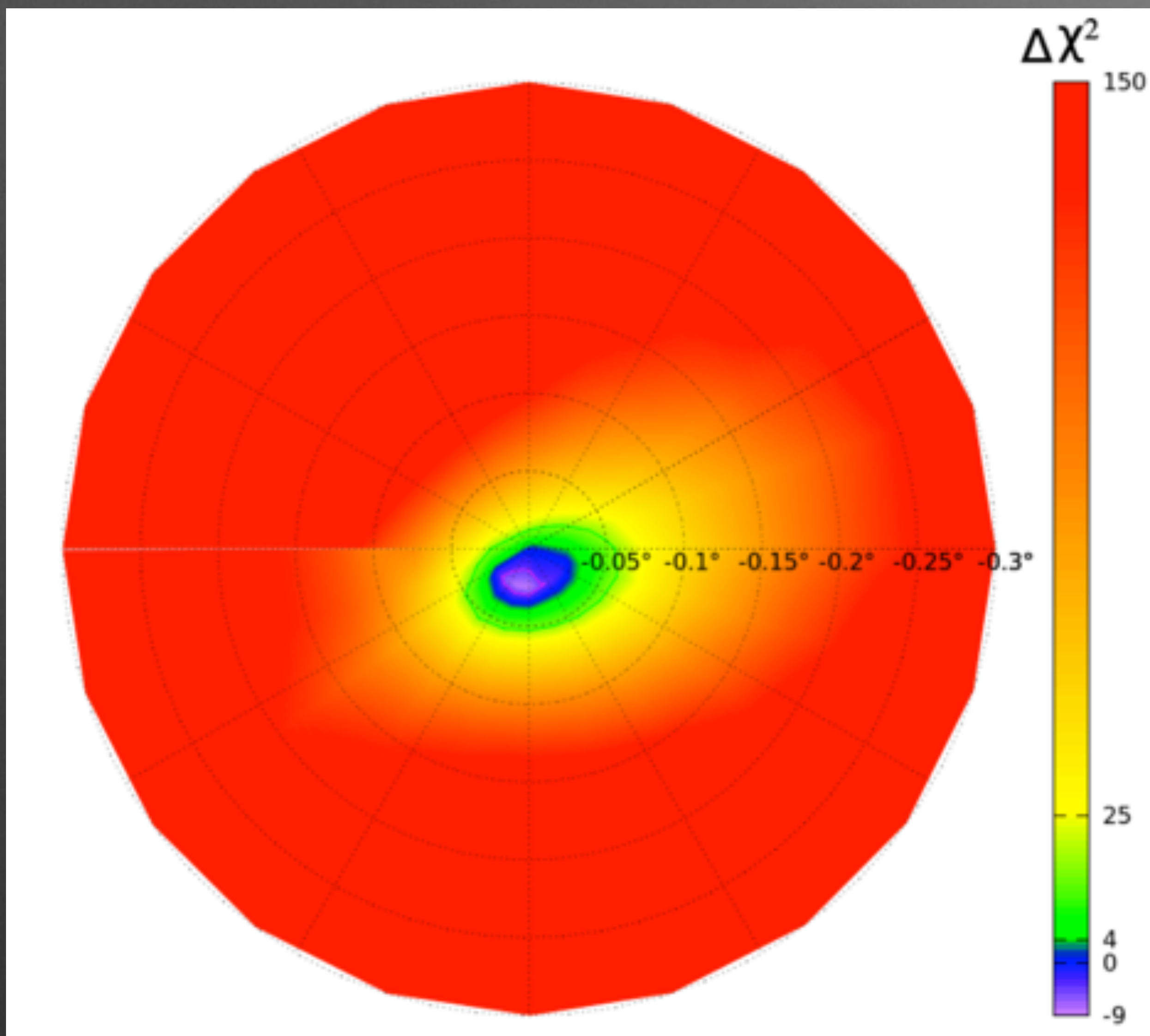
Astrophysical and dark matter interpretations of extended gamma-ray emission from the Galactic Center

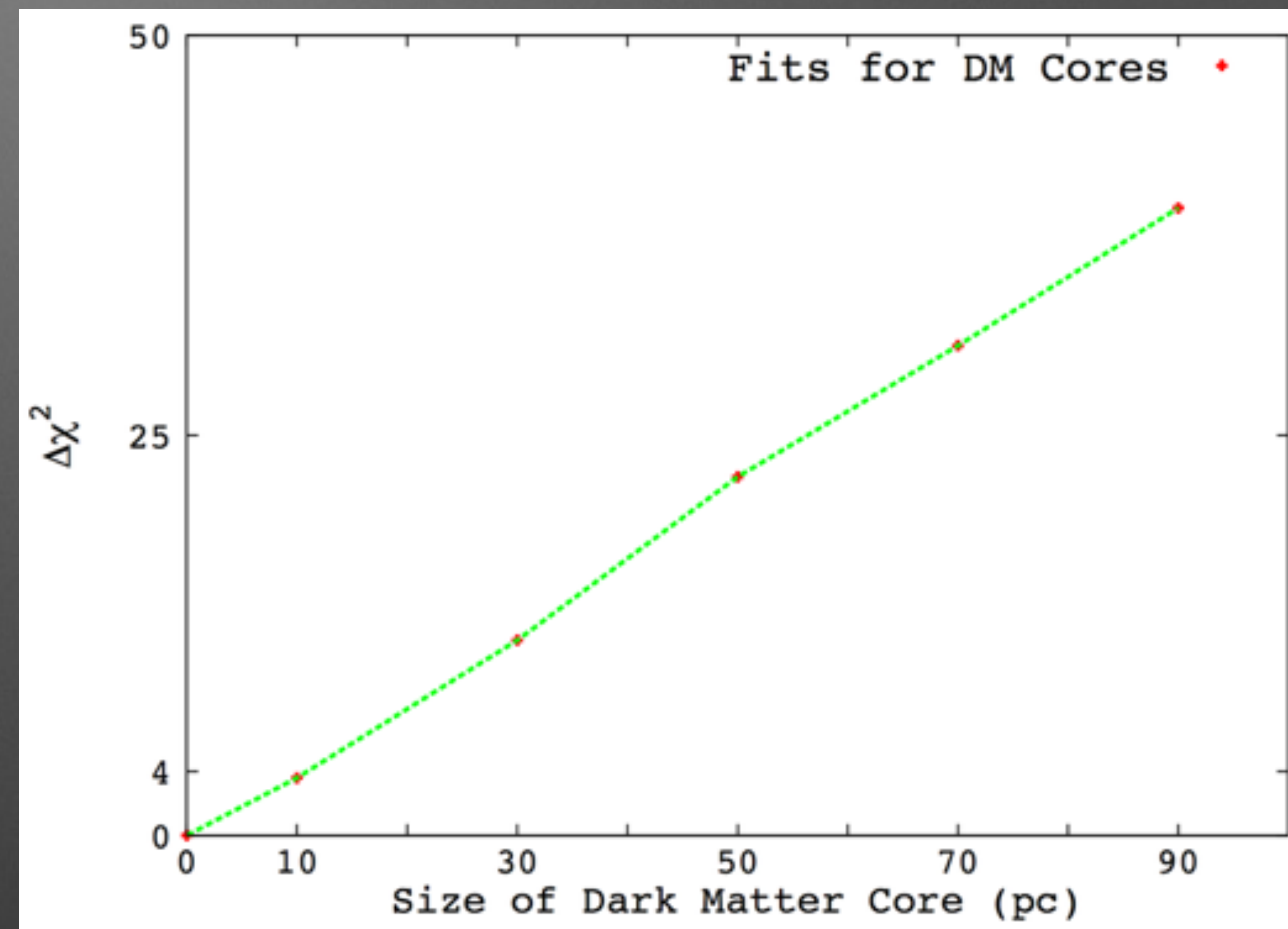
Kevork N. Abazajian,* Nicolas Canac,† Shunsaku Horiuchi,‡ and Manoj Kaplinghat§
Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, Irvine, California 92697 USA

We include point sources from the 2FGL catalog [2] in our ROI, $7^\circ \times 7^\circ$ around the GC centered at $b = 0, \ell = 0$.

their best fit values. The change for $\Delta\gamma = \pm 0.1$ is larger. Fitting a polynomial to the profile likelihood on the variation of γ, we find $\gamma = 1.12 \pm 0.05$ (statistical errors only).

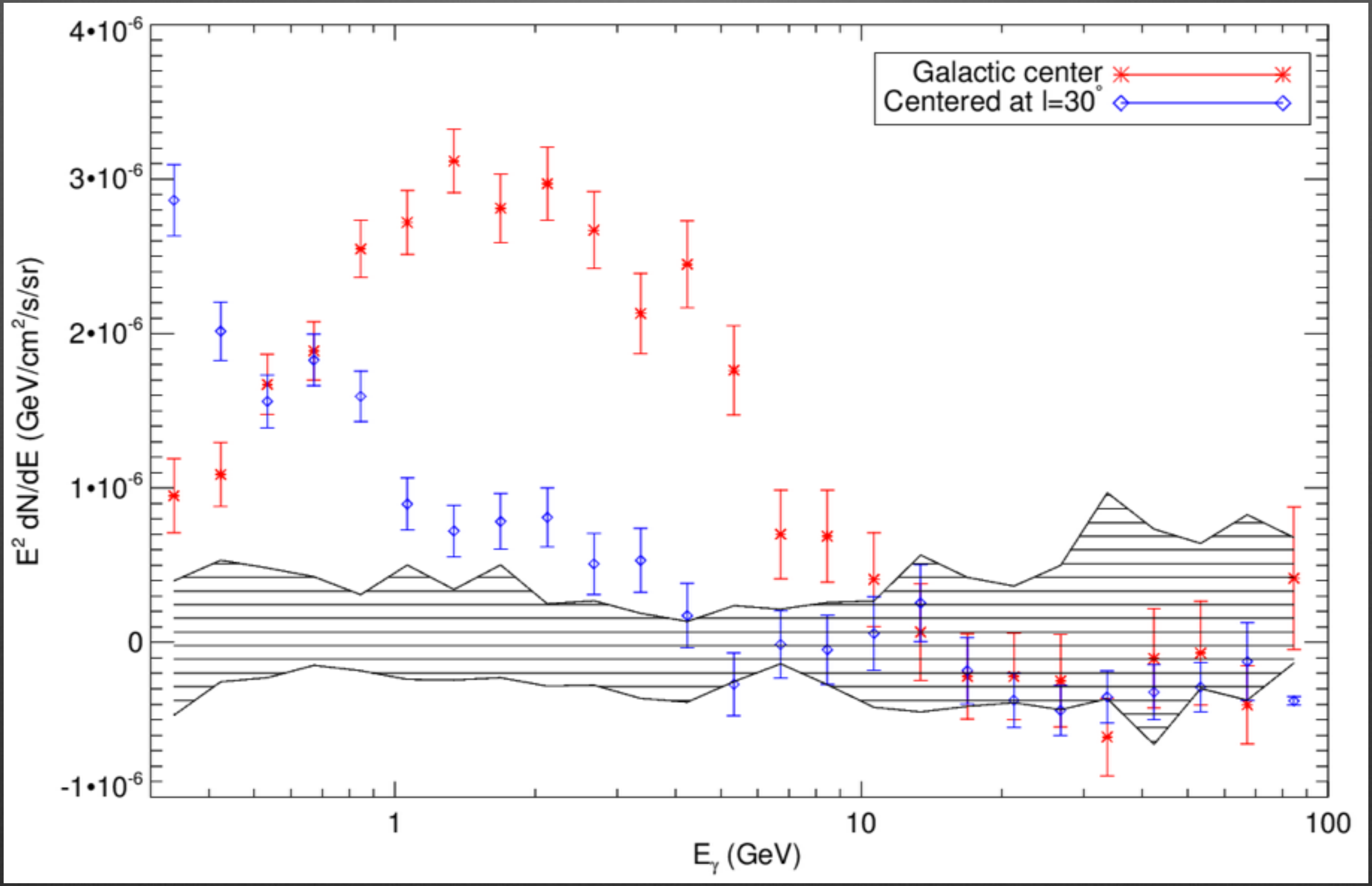
Peaked Towards the Galactic Center





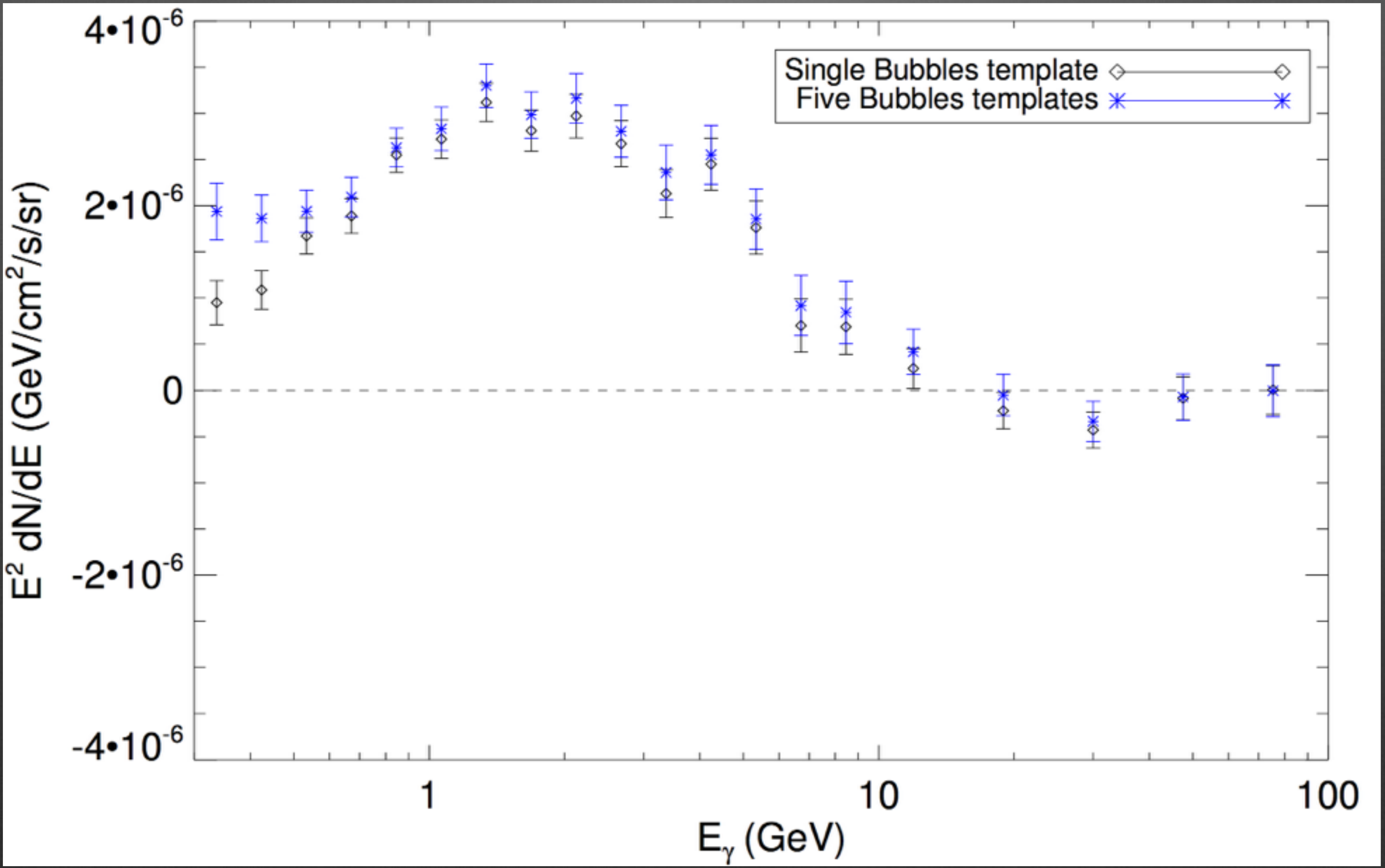
Galactic Center

Comparison To Other Residuals



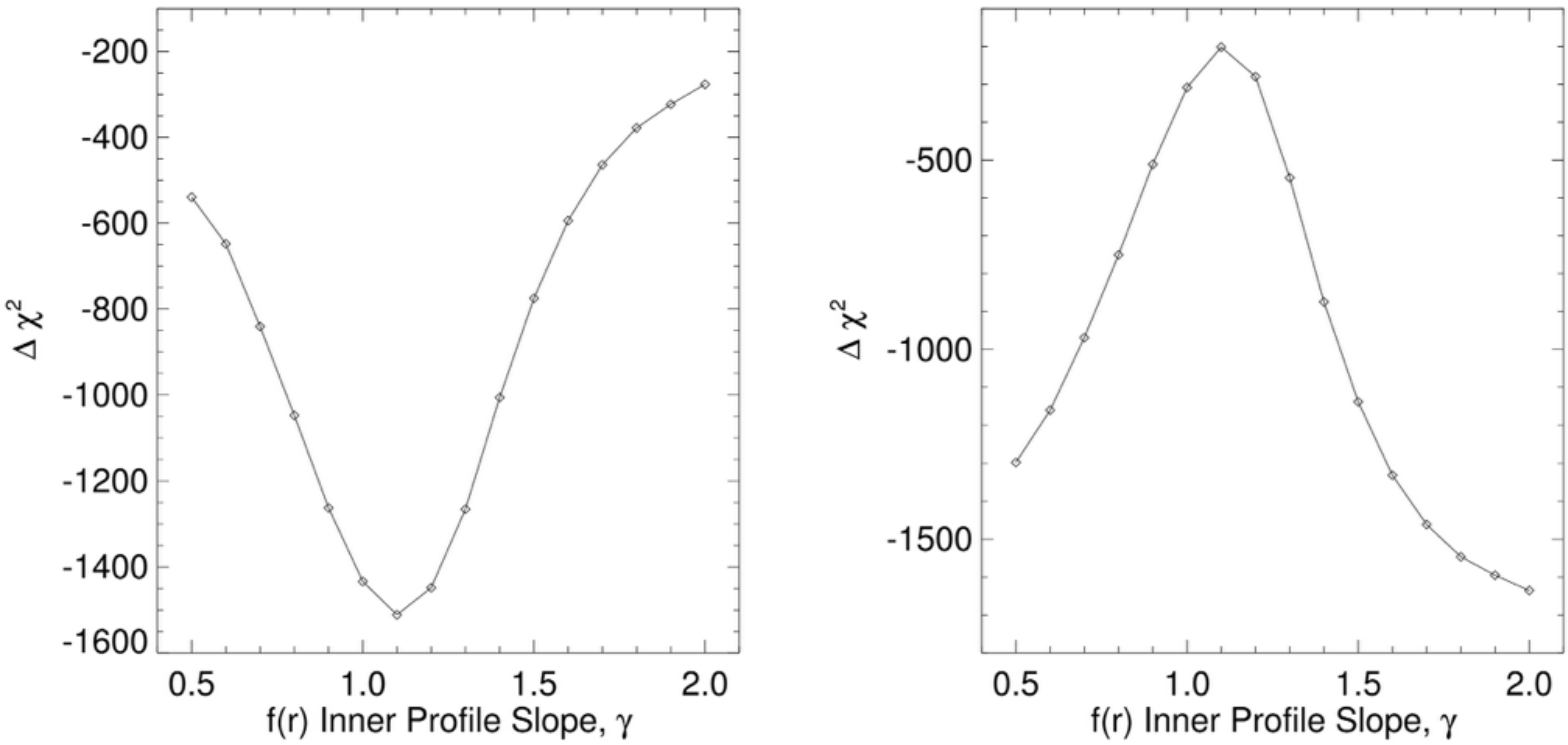
Inner Galaxy

Resilient to Changes in the Fermi Bubbles



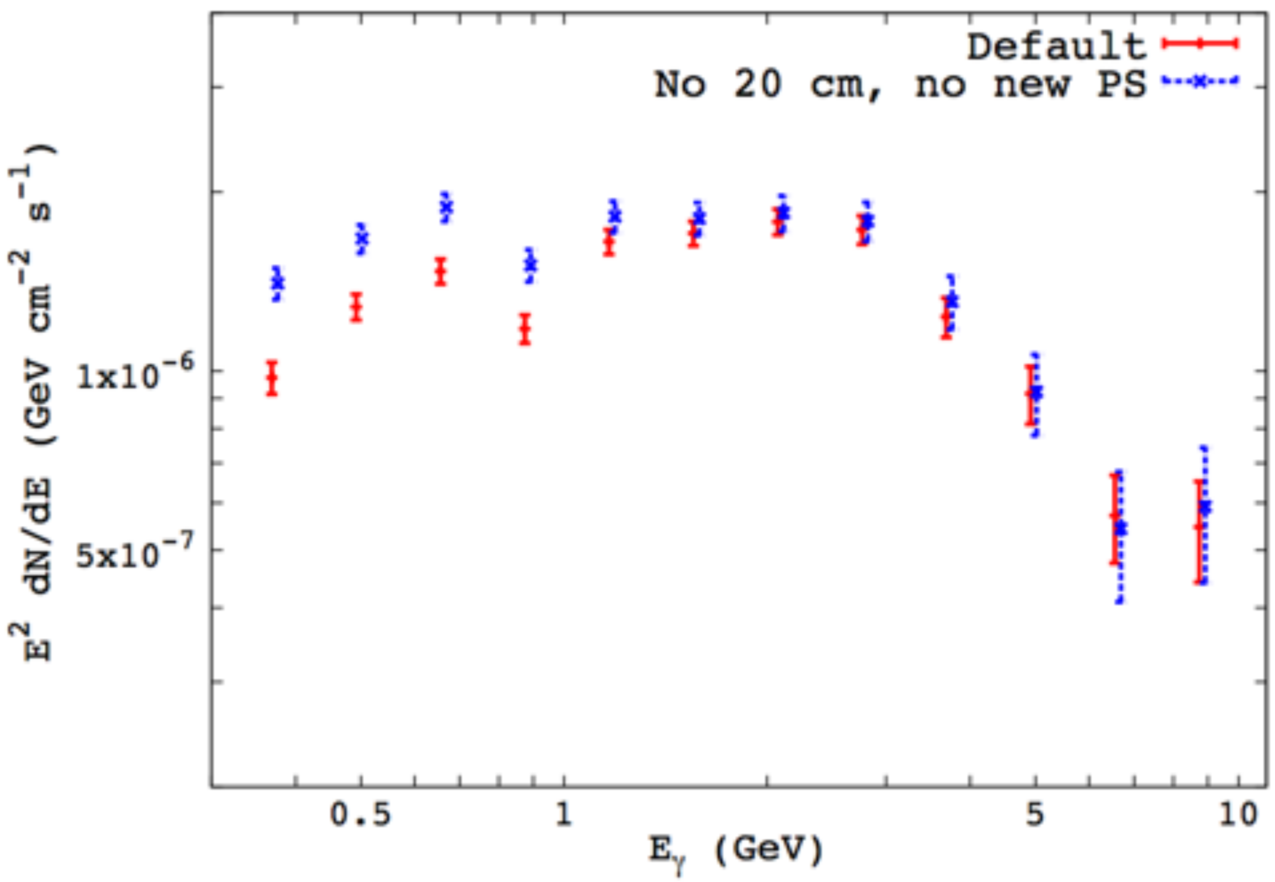
Inner Galaxy

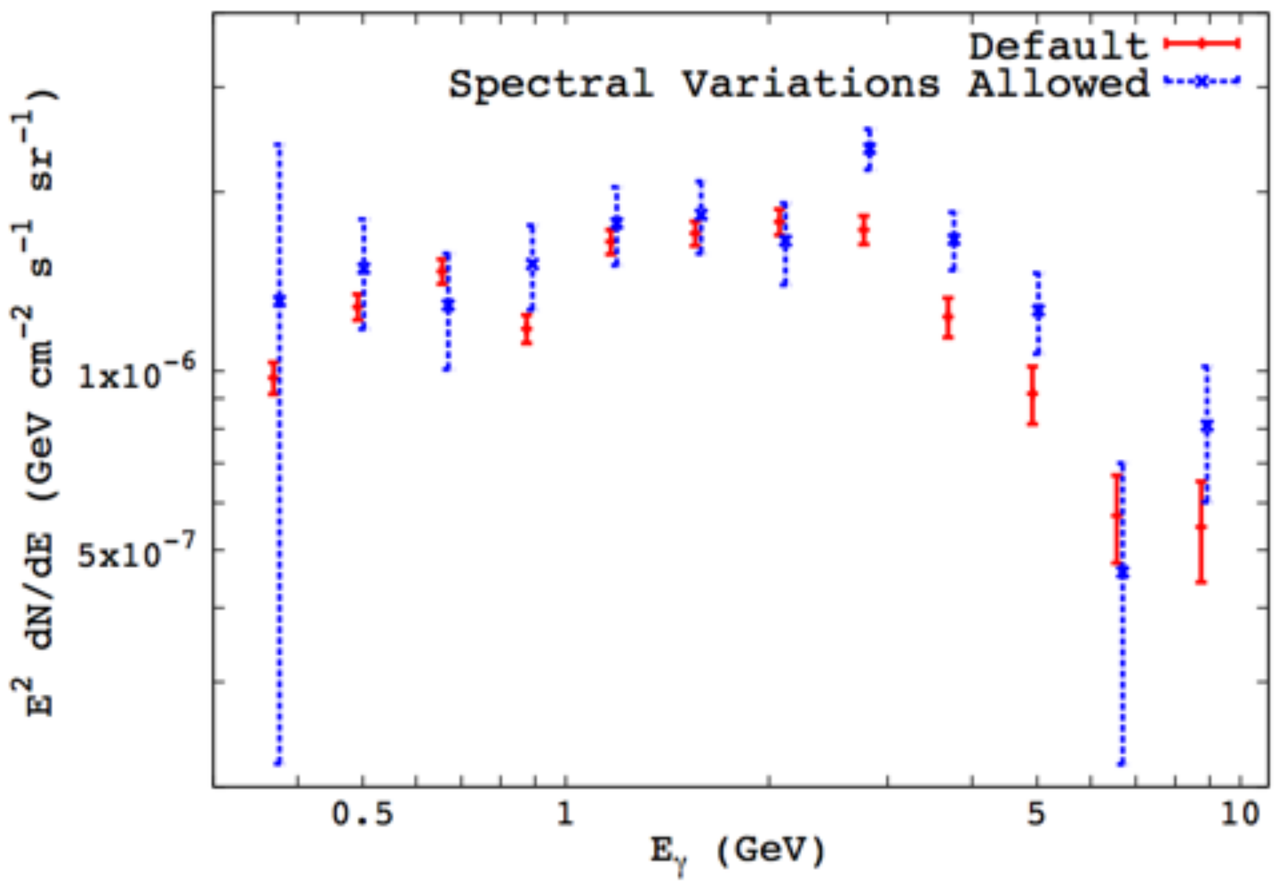
Emission Doesn't Correlate with Gas



Inner Galaxy

Resilient to Diffuse Modeling





Galactic Center

Small Bug

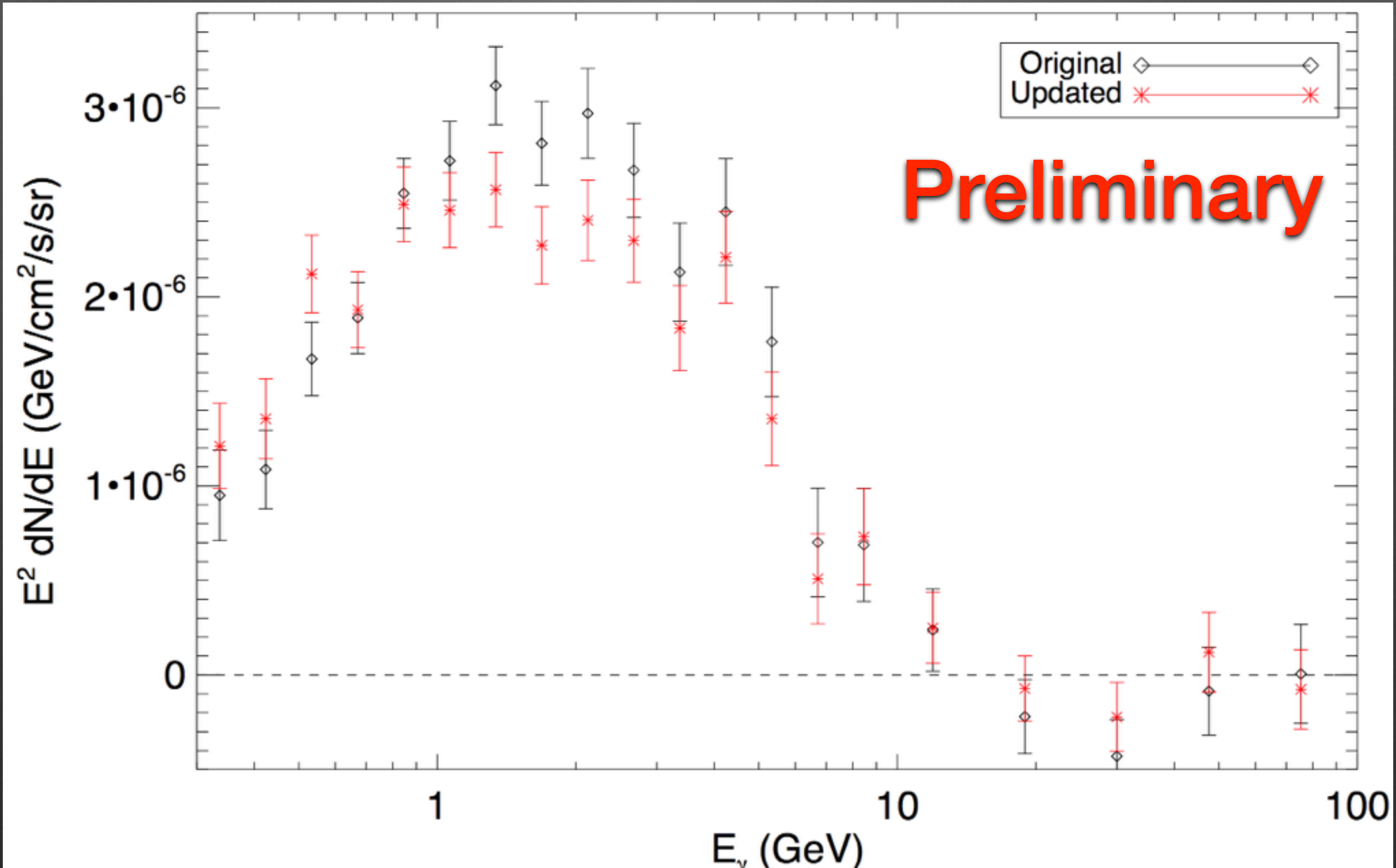
After the work was posted on arXiv a small bug was found in the code for the Inner Galaxy analysis, which affects the smoothing of the diffuse background model

Work is currently ongoing to update the results based on the new model. Early results show that the best fit dark matter cross-sections change by approximately 20%.

Note:

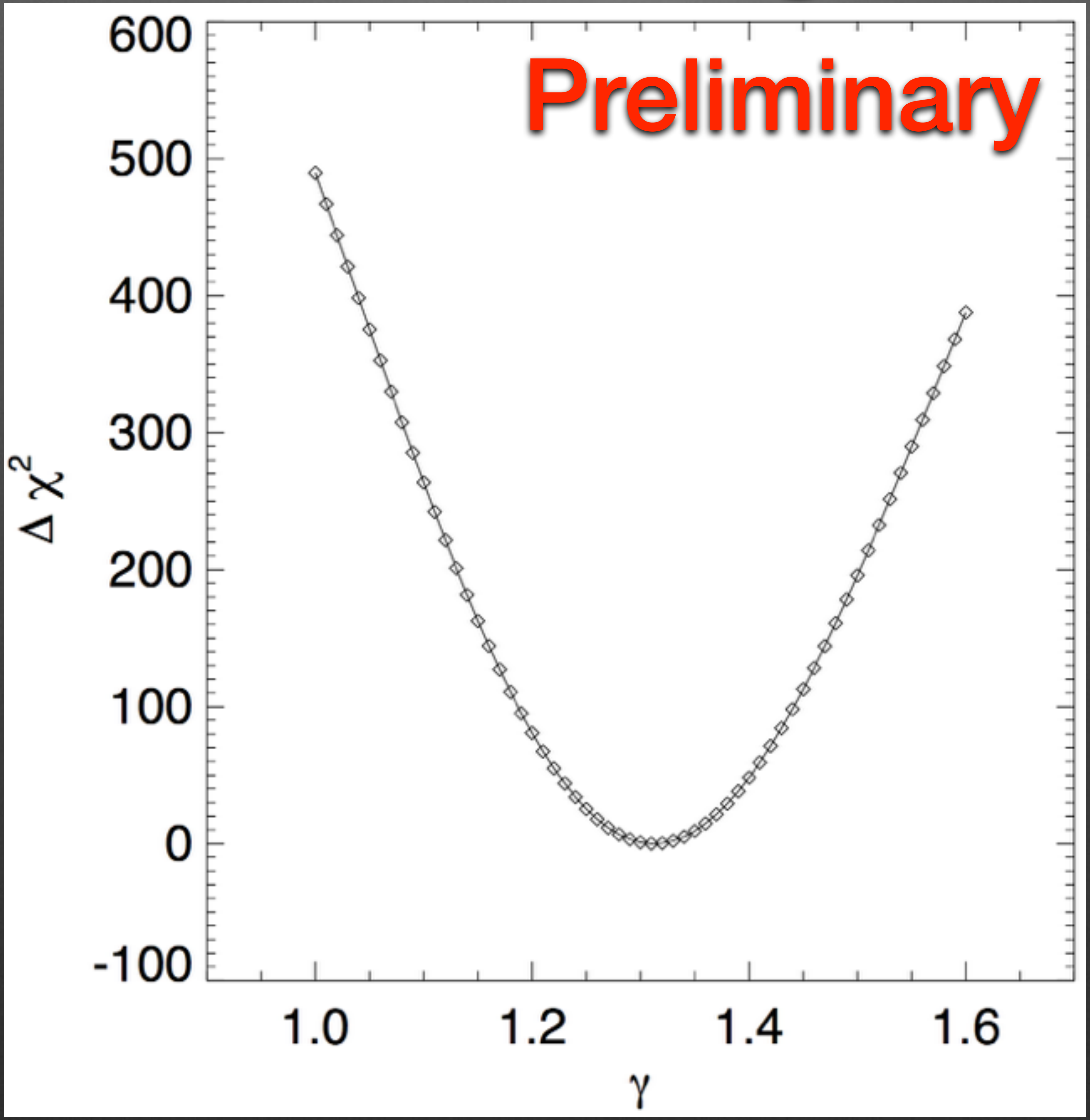
1.) The qualitative conclusions of the paper remain unchanged.
2.) The bug does not affect either the galactic center analysis or the rings fit (on the last slide)

Small Bug

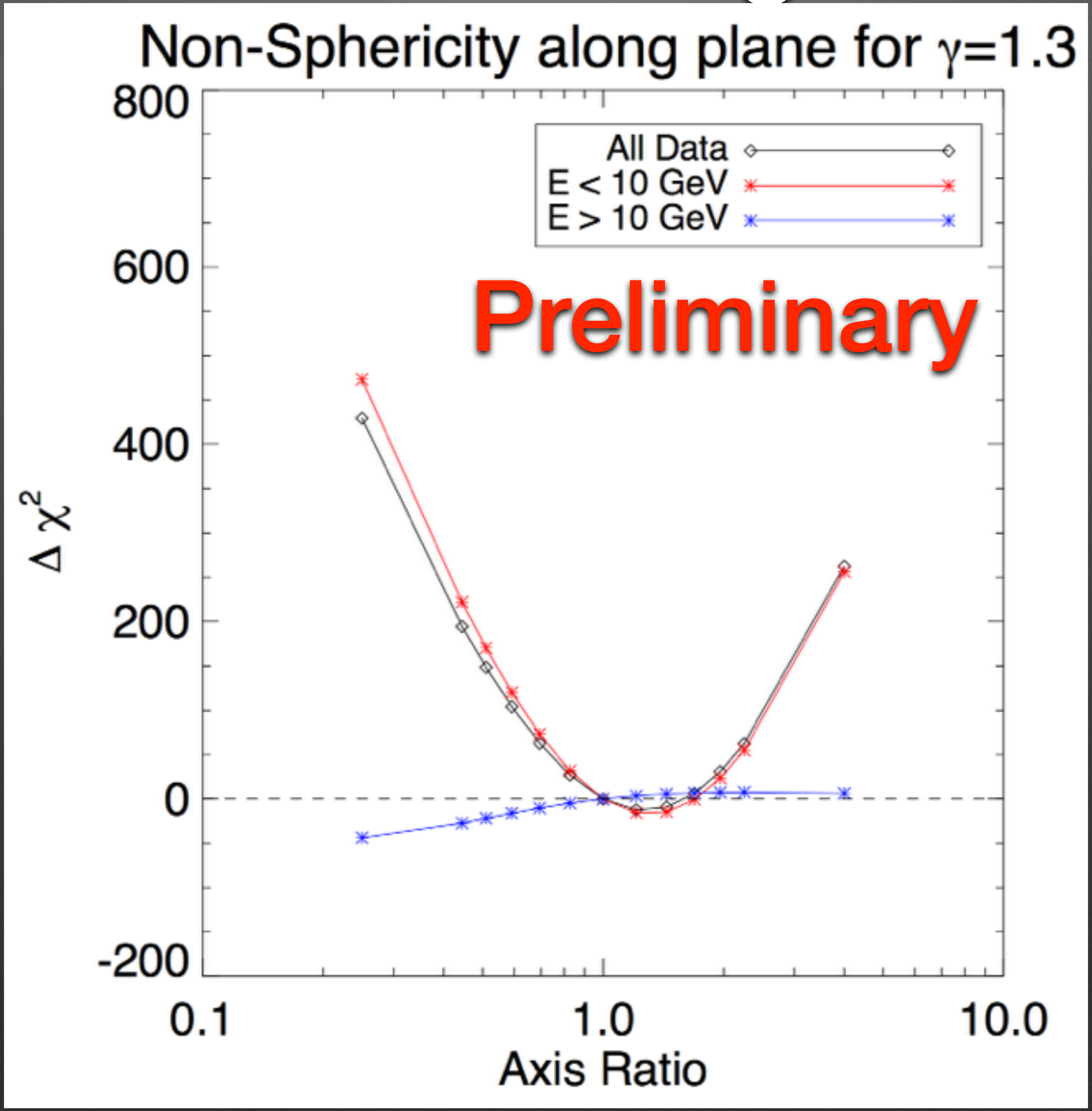


Original
Updated
Preliminary
$3 \cdot 10^{-6}$
$2 \cdot 10^{-6}$
$1 \cdot 10^{-6}$
0
1
10
100
E^2 dN/dE (GeV/cm^2/s/sr)
E_γ (GeV)

Small Bug


Preliminary
600
500
400
300
200
100
0
-100
$\Delta\chi^2$
1.0
1.2
1.4
1.6
γ

Small Bug


Non-Sphericity along plane for γ=1.3
800
600
400
200
0
-200
0.1
1.0
10.0
Axis Ratio
Δ χ²
All Data
E < 10 GeV
E > 10 GeV
Preliminary

Key Features

1.) Bump at an energy ~2 GeV

2.) Extension out to at least 10^{o}

3.) Spherical Symmetry (to within 20-30%)

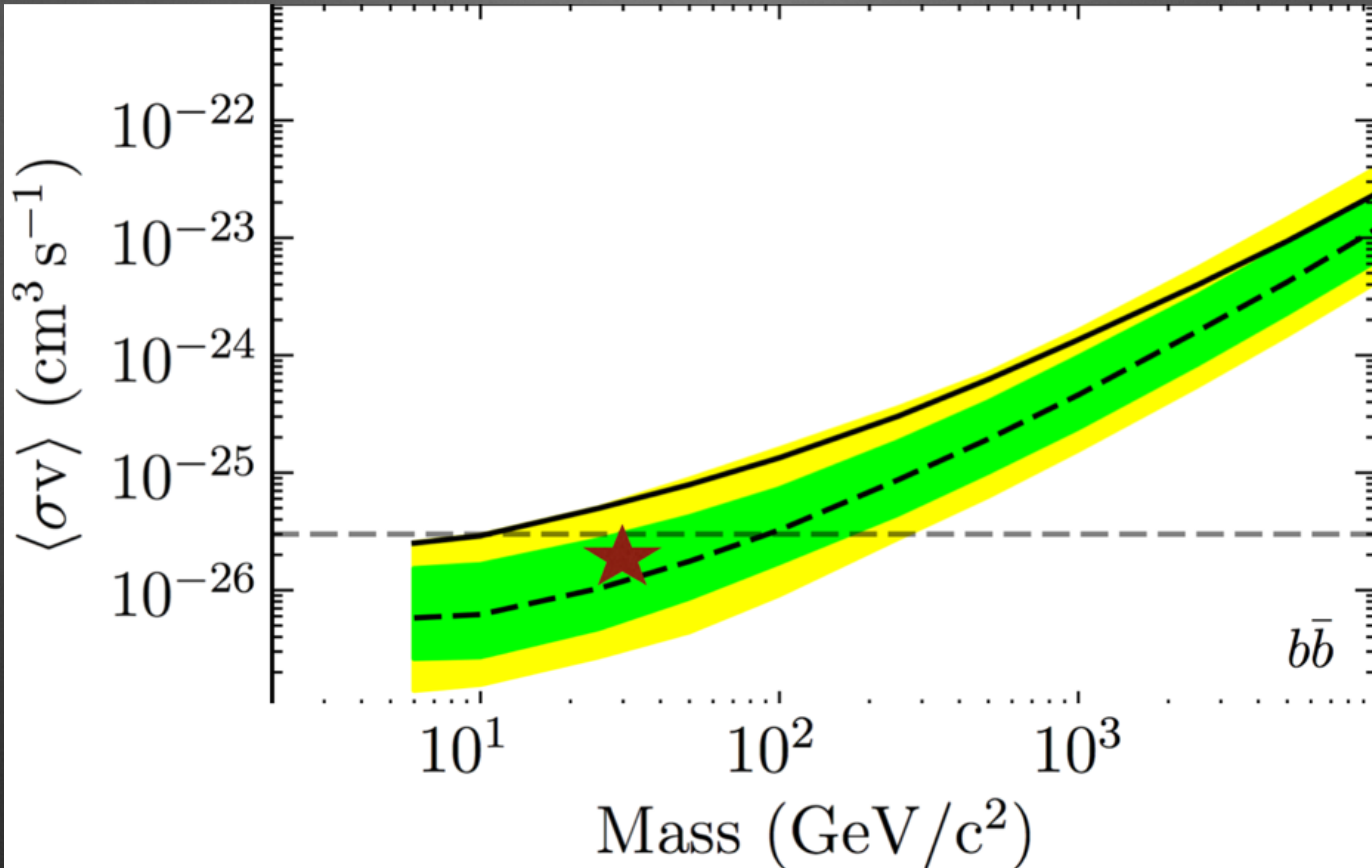
4.) Centered to within 0.05^{o} of the GC, and continues to increase to within 0.07^{o}

5.) Not correlated with gas, not due to spectral errors in background templates,

Non-Dark Matter Explanations

- Several Models have been proposed to explain the excess
  - An undetected population of **MSPs** (Abazajian et al. 2011)
  - Transient **Outbursts** from the Galactic Center
    - **Hadronic** (Carlson & Profumo 2014)
    - **Leptonic** (Petrovic et al. 2014)

Future Indirect Tests - Dwarf Galaxies

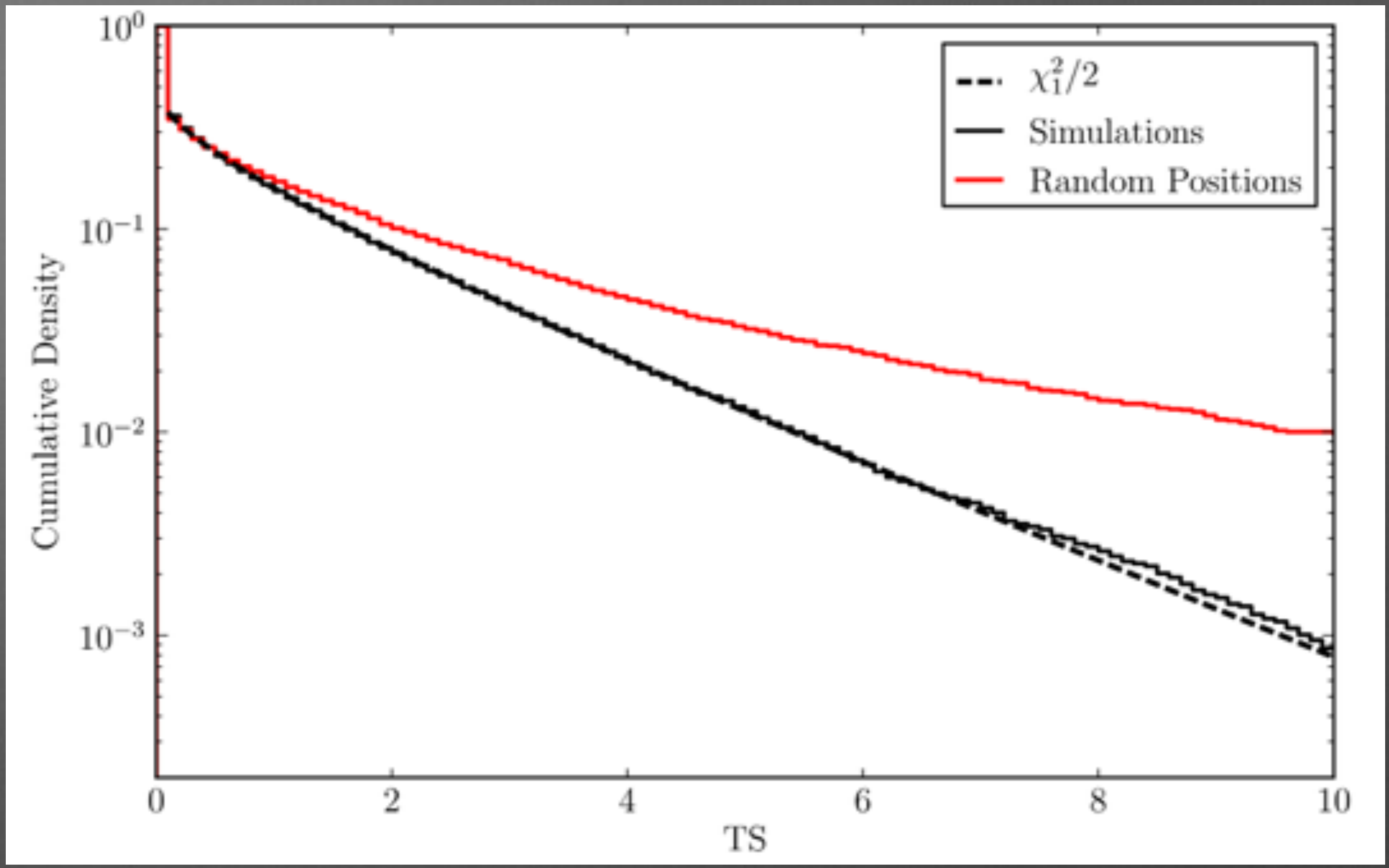


The Fermi-LAT Collaboration (2013)

Future Indirect Tests - Dwarf Galaxies

- Fermi-LAT collaboration finds a TS=8.7 for a 25 GeV dark matter particle annihilation to b-quarks

- Interpreted as a Poisson signal, this would correlate to 2.95σ



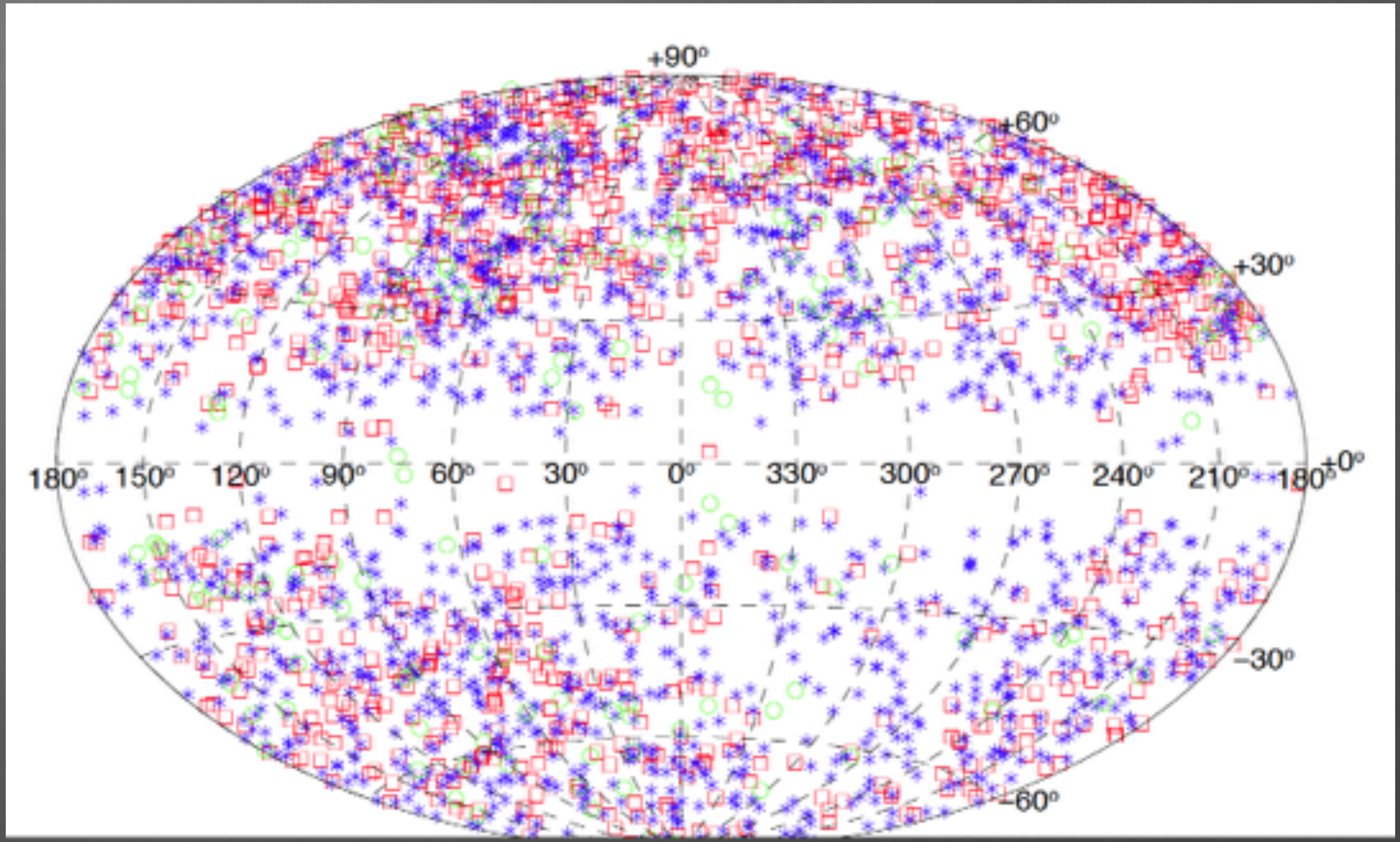
The Fermi-LAT Collaboration (2013)

- However, the significance of this excess is mitigated by the observed probability of finding hotspots in blank sky locations

- This decreases the local significance to 2.2σ

Future Indirect Tests - Dwarf Galaxies

However, multi wavelength studies can tell you a lot about which sources are likely to contribute at low TS values

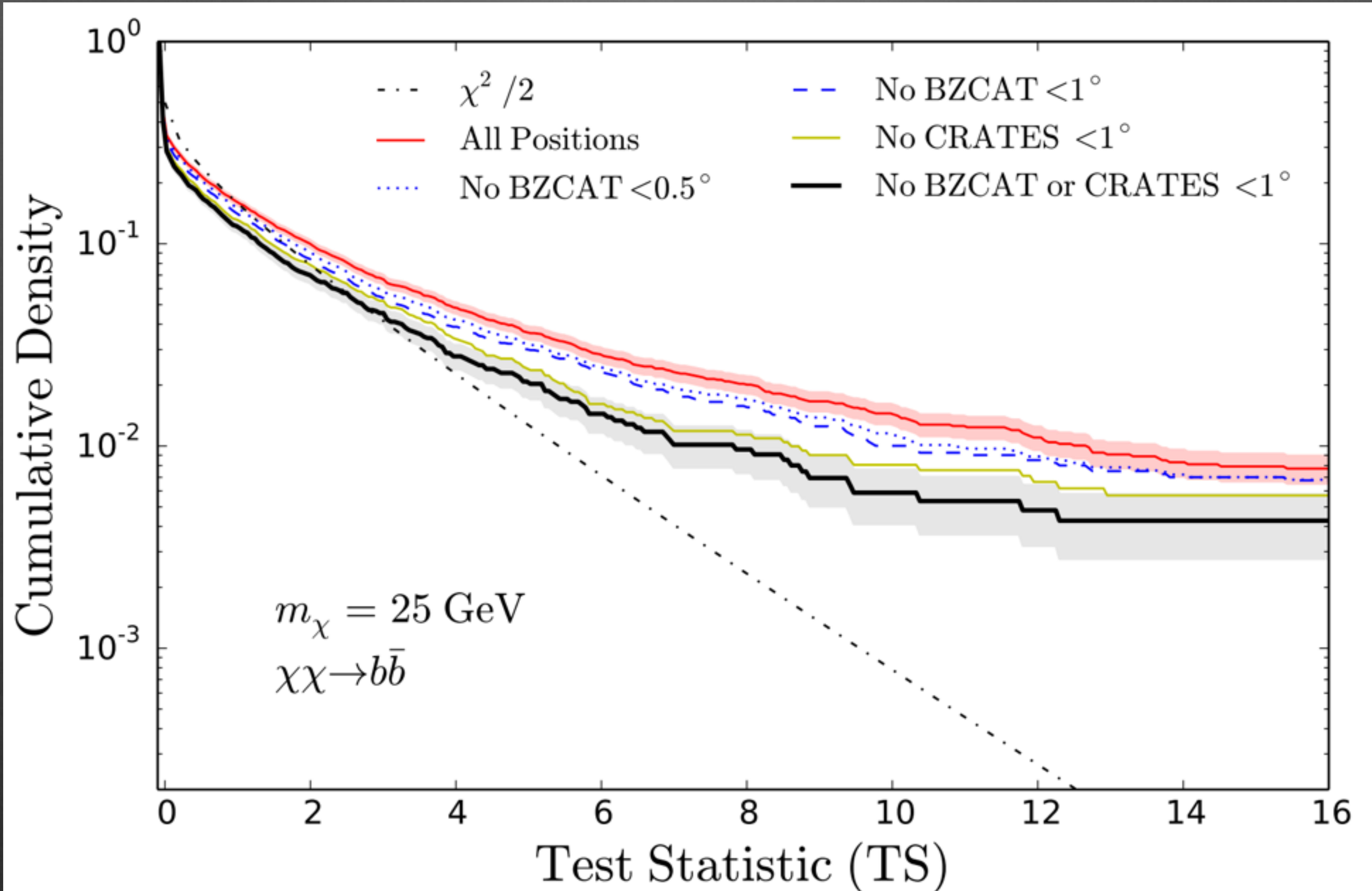


BZCAT Catalog 3149 Sources

Use the BZCAT and CRATES catalogs to tell you about the positions of probable gamma-ray sources

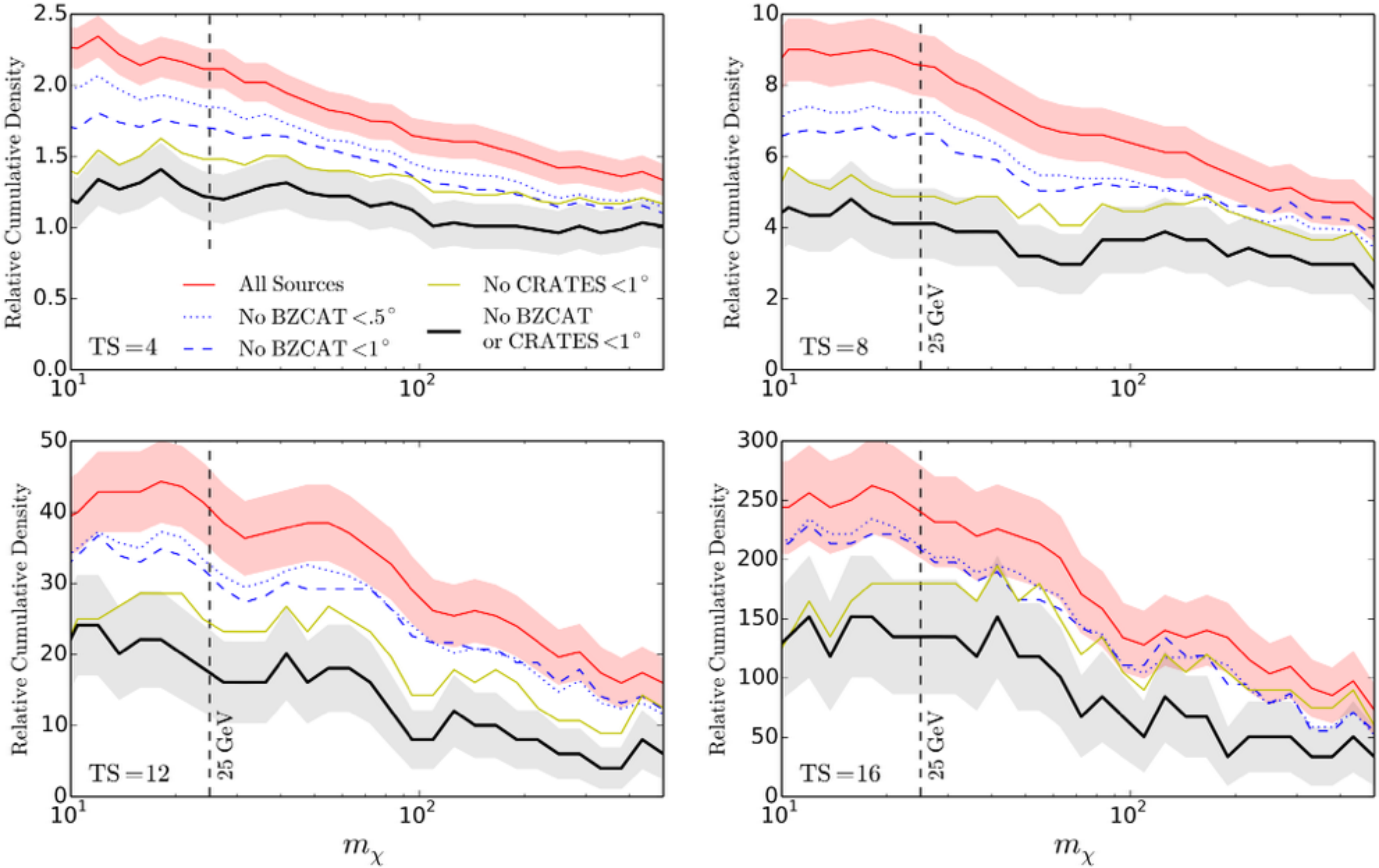
Carlson, Hooper, Linden (2014)

Future Indirect Tests - Dwarf Galaxies



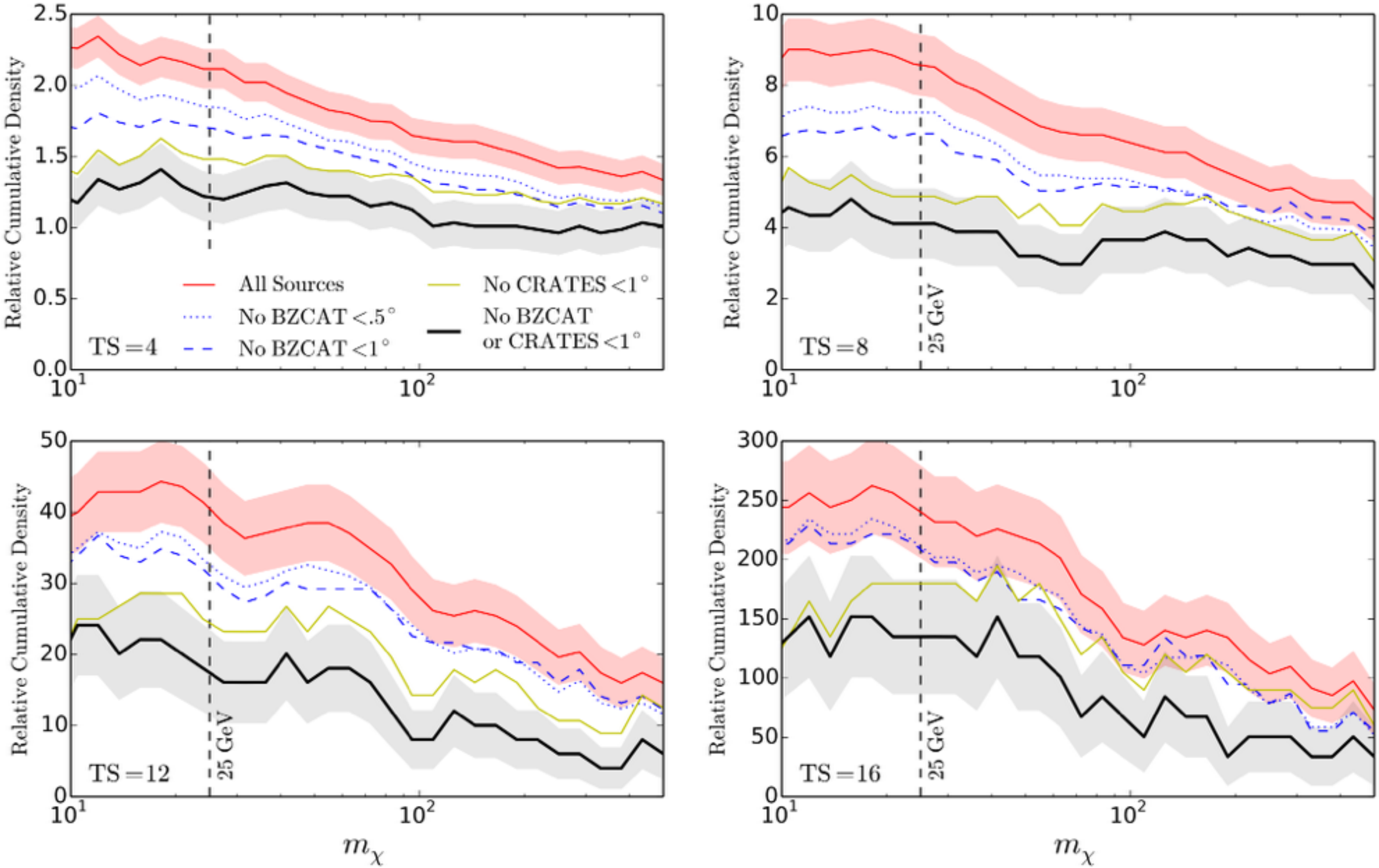
Carlson, Hooper, Linden (2014)

Future Indirect Tests - Dwarf Galaxies



Carlson, Hooper, Linden (2014)

Future Indirect Tests - Dwarf Galaxies



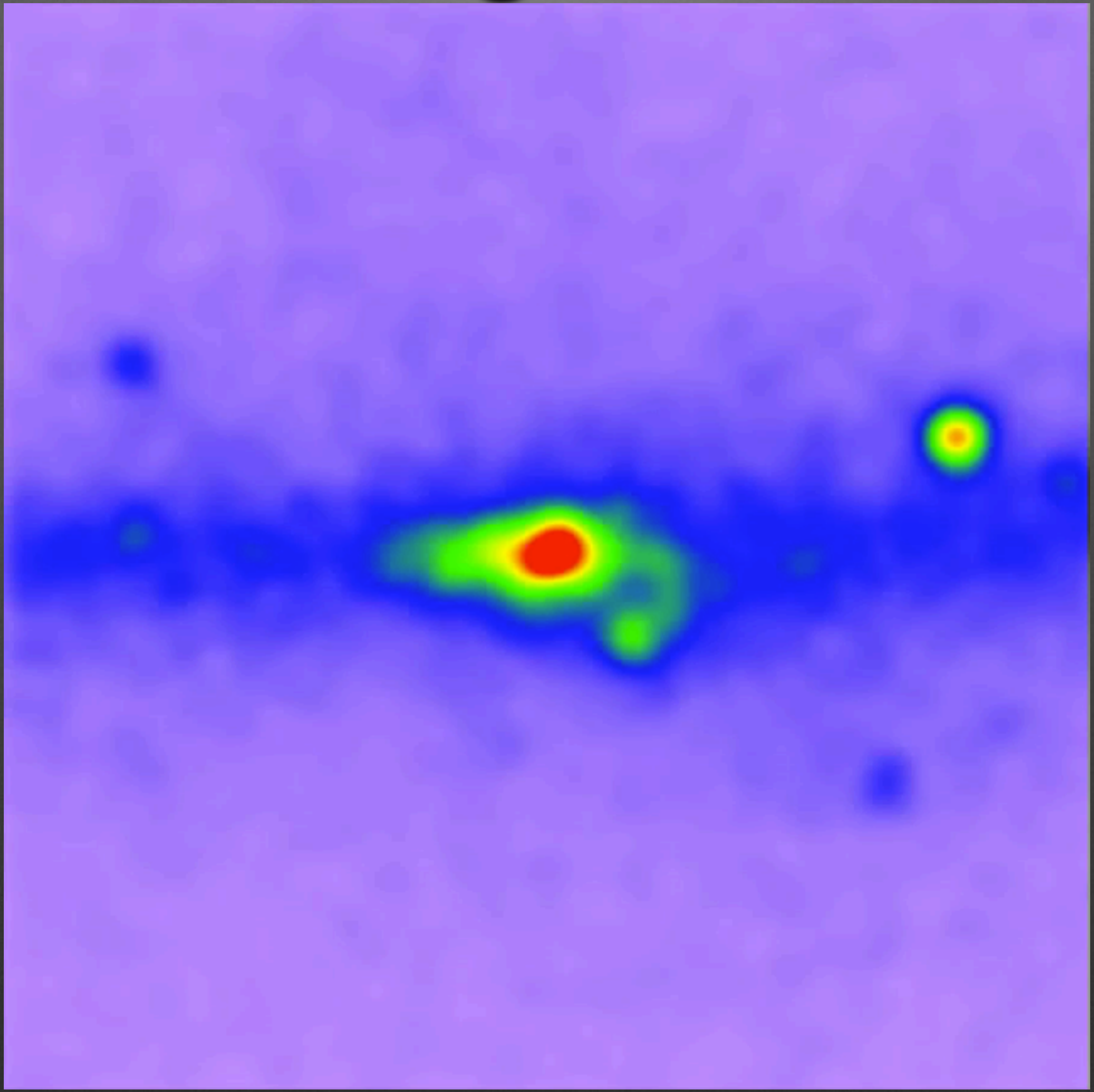
Carlson, Hooper, Linden (2014)

Future Indirect Tests - Dwarf Galaxies

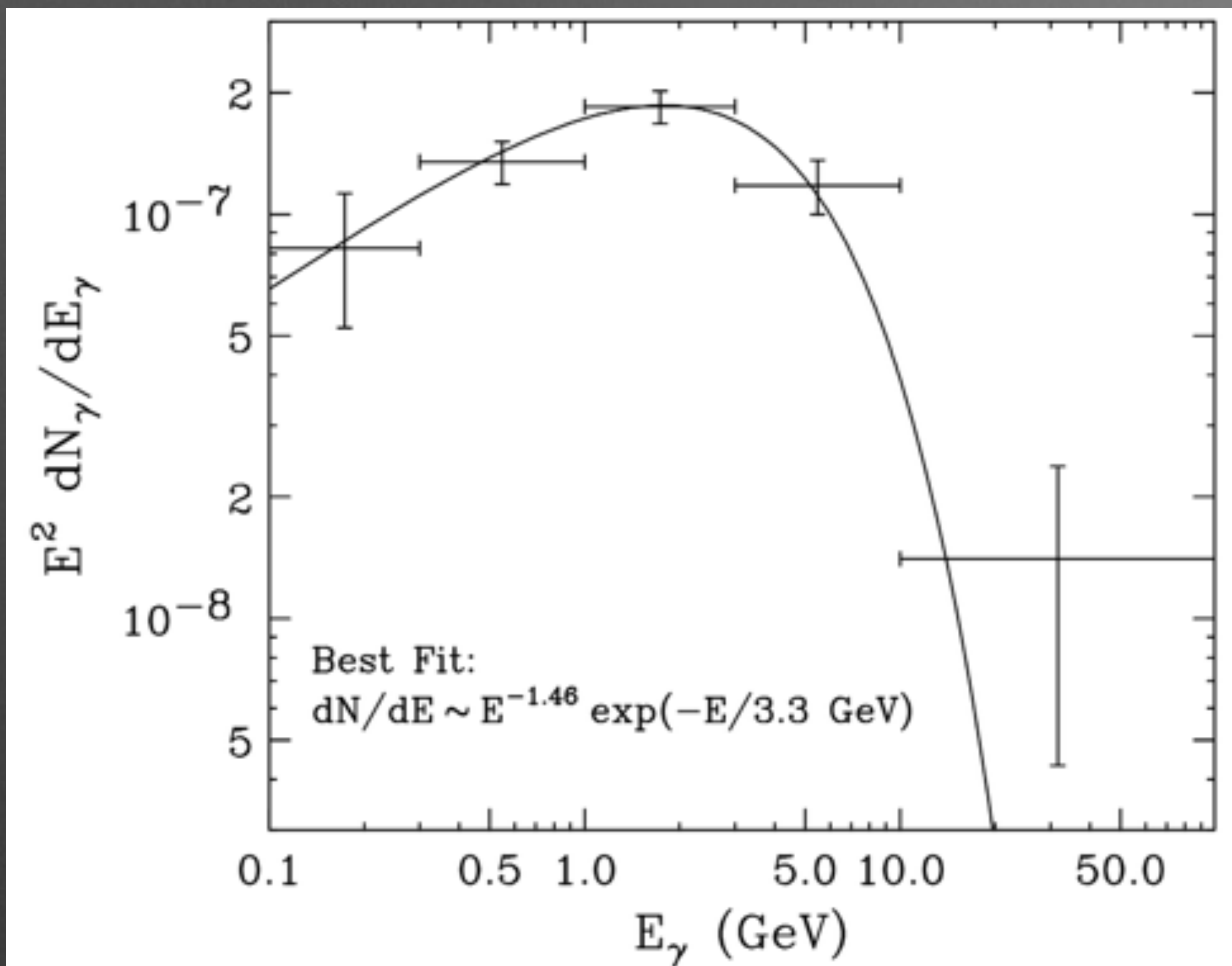
dSph	Nearby Blazars (Distance to dSph °)
Bootes 1	J1359+1436 (.13) J1401+1350 (.74) J140136+151303 (0.80)
Bootes 3	J135948+270834 (0.71)
Canes Venatici 1	J132457+325160 (0.97)
Draco	J1715+5724 (0.85)
Hercules	J162737+121550 (0.95)
Leo 4	J1133+0015 (0.80) J113631-005250 (0.98)
Leo 5	J1131+0234 (.40) J1132+0237 (.58) J112940+021817 (0.38)
Pisces 2	J225823+051634 (0.68) J230153+060906 (0.87)
Sculptor	J0100-3337* (0.04) J010107-334758 (0.24) J005817-334755 (0.41) J005819-341957 (0.76) J010307-342458 (0.97)
Segue 1	J100955+160223 (0.70)
Sextans	J1010-0200* (0.70) J101454-005506 (0.82)
Ursa Major 1	J103034+513236 (0.77)
Ursa Major 2	J0854+6218* (0.91)
Willman 1	J1048+5009 (0.87)

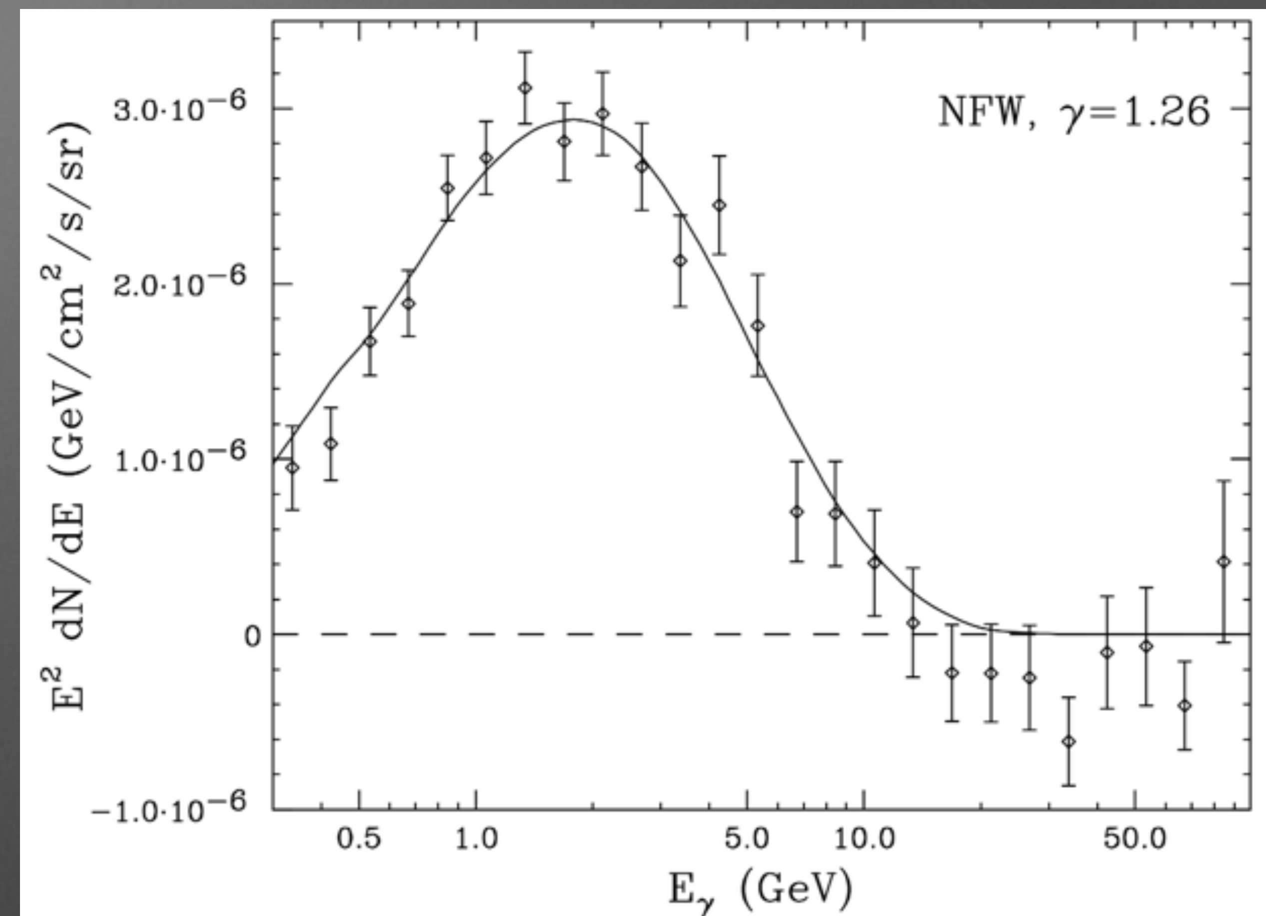
Carlson, Hooper, Linden (2014)

Signal!



Why Could it be MSPs?

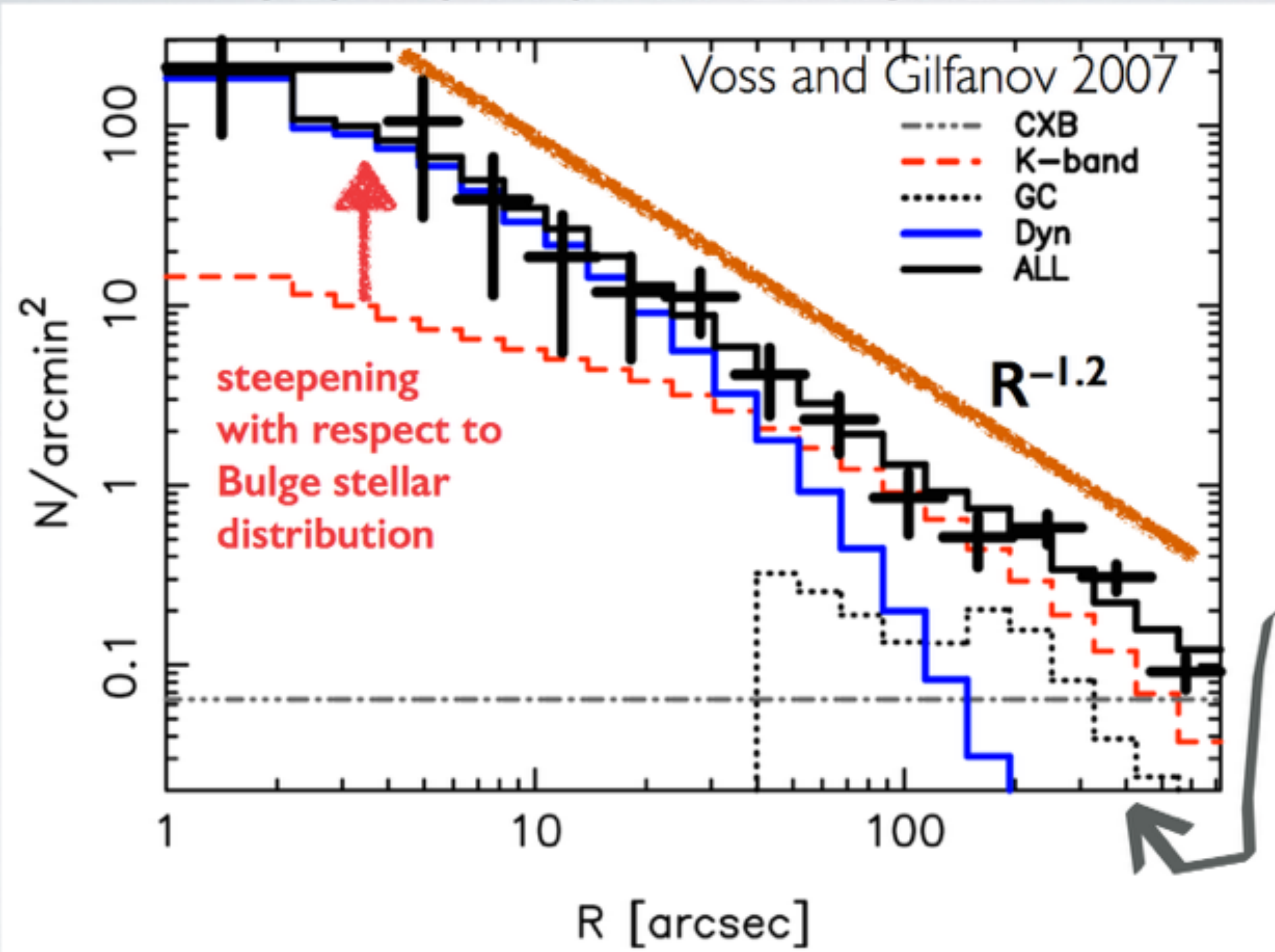




Hooper et al. (2013)

Why Could it be MSPs?

DEGENERACY WITH MILLI-SECOND PULSARS IN SPATIAL PROFILE



We make the reasonable assumption that Low-Mass X-ray Binaries have the same spatial distribution as MSPs

400" towards M31 center = 1.5 kpc distance from center = 10 degrees towards MW center

Orange line is same as best-fit excess template ($R^{-1.2}$ in projection implies $r^{-2.2}$ de-projected)!

Slide from Manoj Kaplinghat

FERMILAB-PUB-14-236-A

A New Determination of the Spectra and Luminosity Function of Gamma-Ray Millisecond Pulsars

Ilias Cholis,[1] Dan Hooper,[1,2] and Tim Linden[3]

[1] *Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, IL*
[2] *University of Chicago, Department of Astronomy and Astrophysics, 5640 S. Ellis Ave., Chicago, IL*
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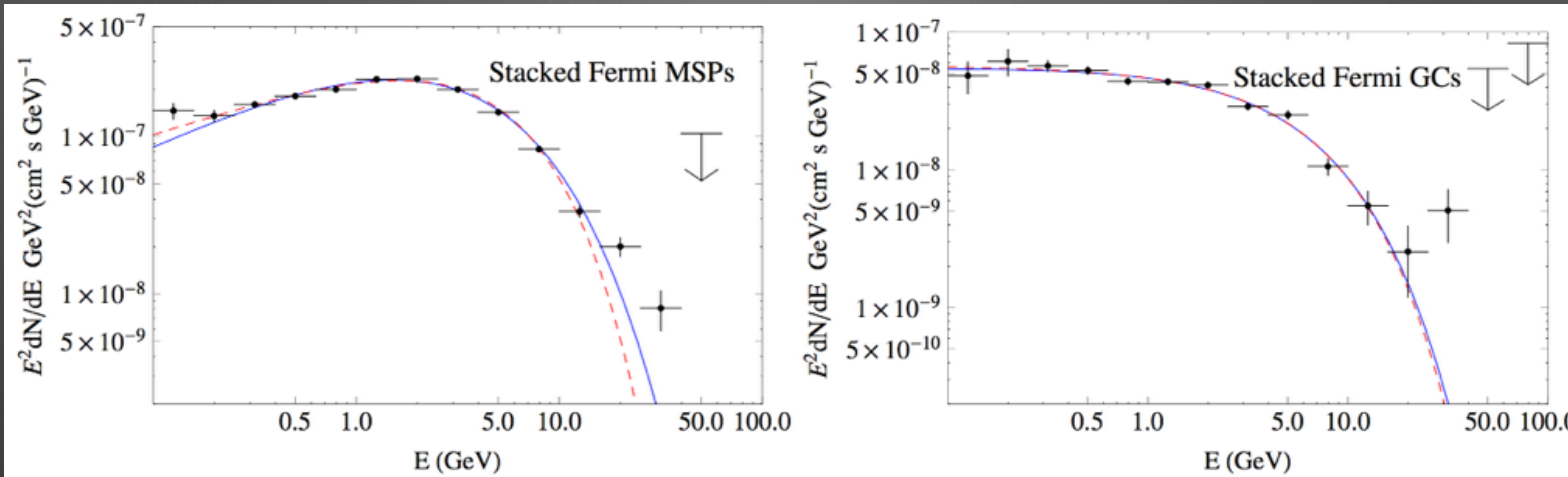
(Dated: July 22, 2014)

In this article, we revisit the gamma-ray emission observed from millisecond pulsars and globular clusters. Based on 5.6 years of data from the Fermi Gamma-Ray Space Telescope, we report gamma-ray spectra for 61 millisecond pulsars, finding most to be well fit by a power-law with an exponential cutoff, producing to a spectral peak near ~1-2 GeV (in E^2dN/dE units). Additionally, while most globular clusters exhibit a similar spectral shape, we identify a few with significantly softer spectra. We also determine the gamma-ray luminosity function of millisecond pulsars using the population found in the nearby field of the Milky Way, and within the globular cluster 47 Tucanae. We find that the gamma-ray emission observed from globular clusters is dominated by a relatively small number of bright millisecond pulsars, and that low-luminosity pulsars account for only a small fraction of the total flux. Our results also suggest that the gamma-ray emission from millisecond pulsars is more isotropic and less strongly beamed than the emission at X-ray wavelengths. Furthermore, the observed distribution of apparent gamma-ray efficiencies provides support for the slot gap or the outer gap models over those in which the gamma-ray emission originates from regions close to the neutron star's magnetic poles (polar cap models).

PACS numbers: 97.60.Gb, 95.55.Ka, 98.70.Rz

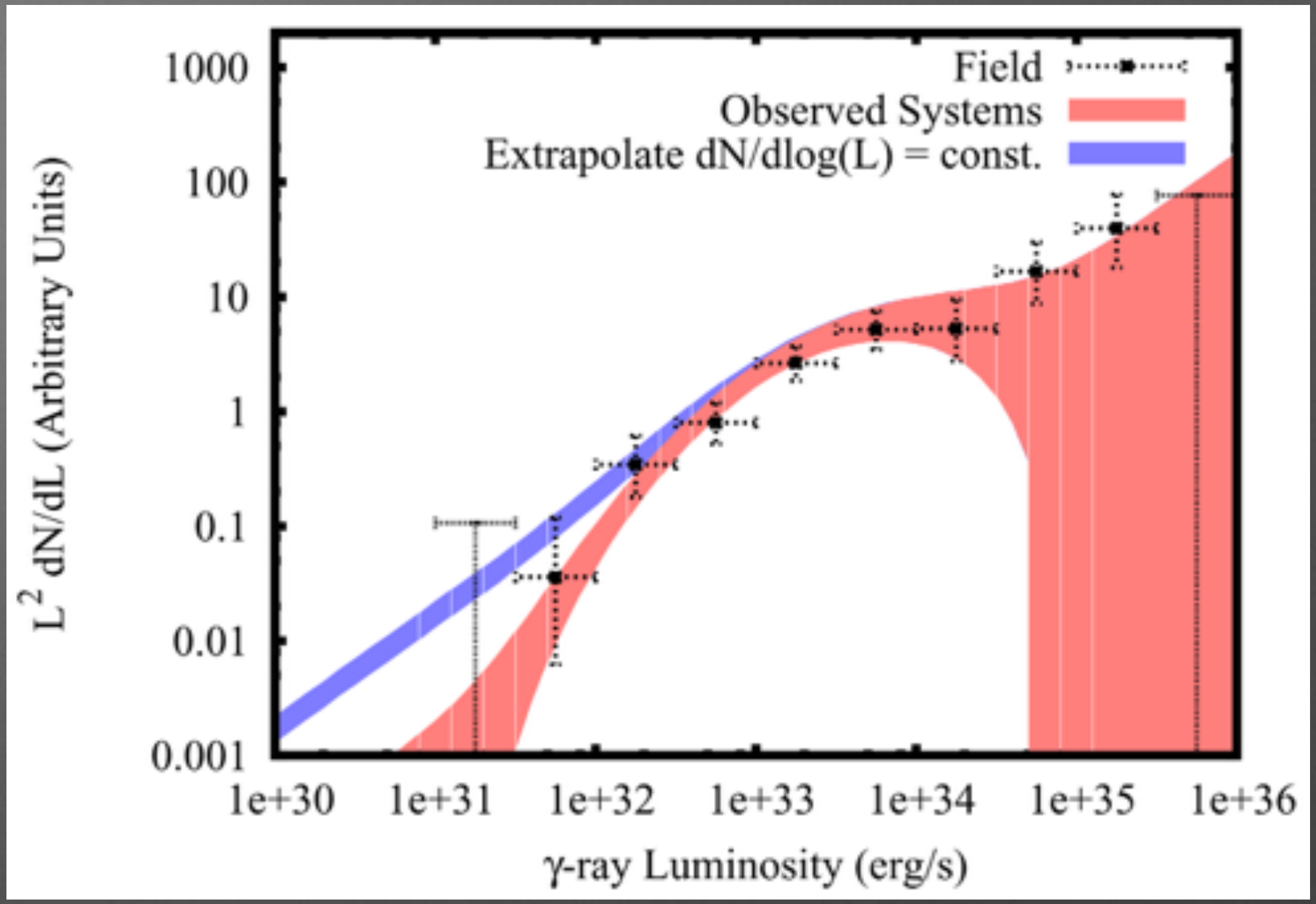
Millisecond Pulsars

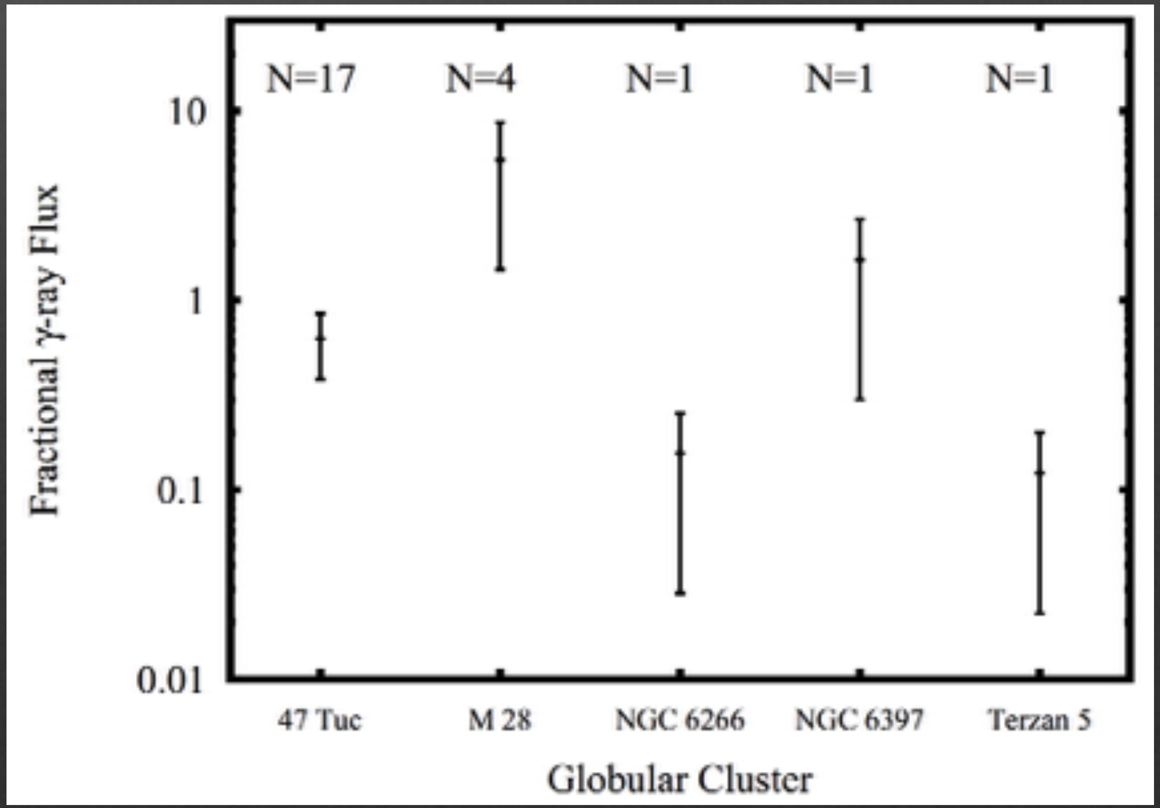


Fermi observations allow us to study the spectrum of the millisecond pulsar population

Millisecond Pulsars

- We can also calculate the luminosity function of MSPs
- Two methods are used, one based on the population of field MSPs, and the other based on the population of X-Ray bright MSPs detected in the globular cluster 47 Tuc.





Cholis et al. (2014)

Millisecond Pulsars

FERMILAB-14-240-A

Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars

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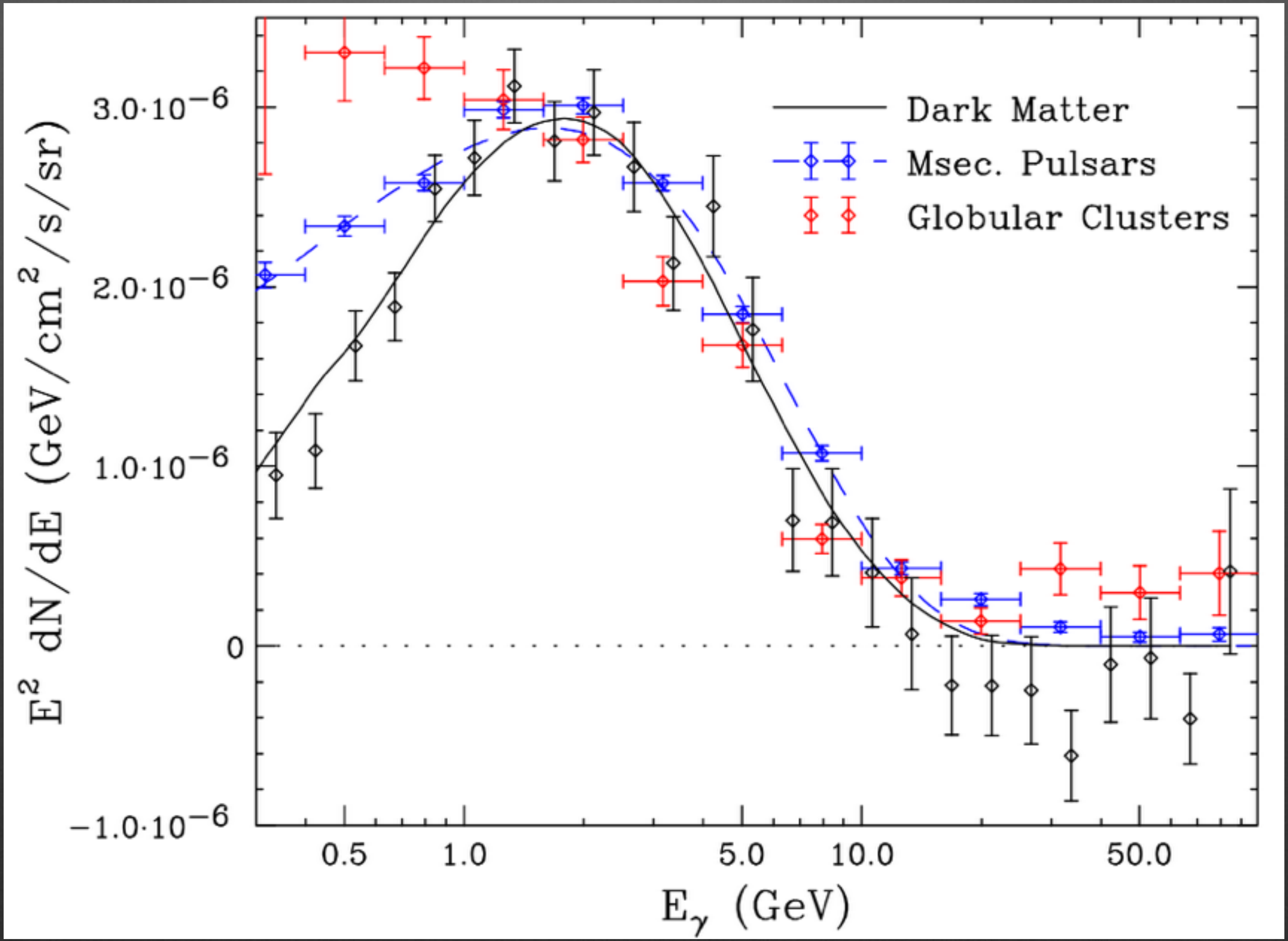
(Dated: July 23, 2014)

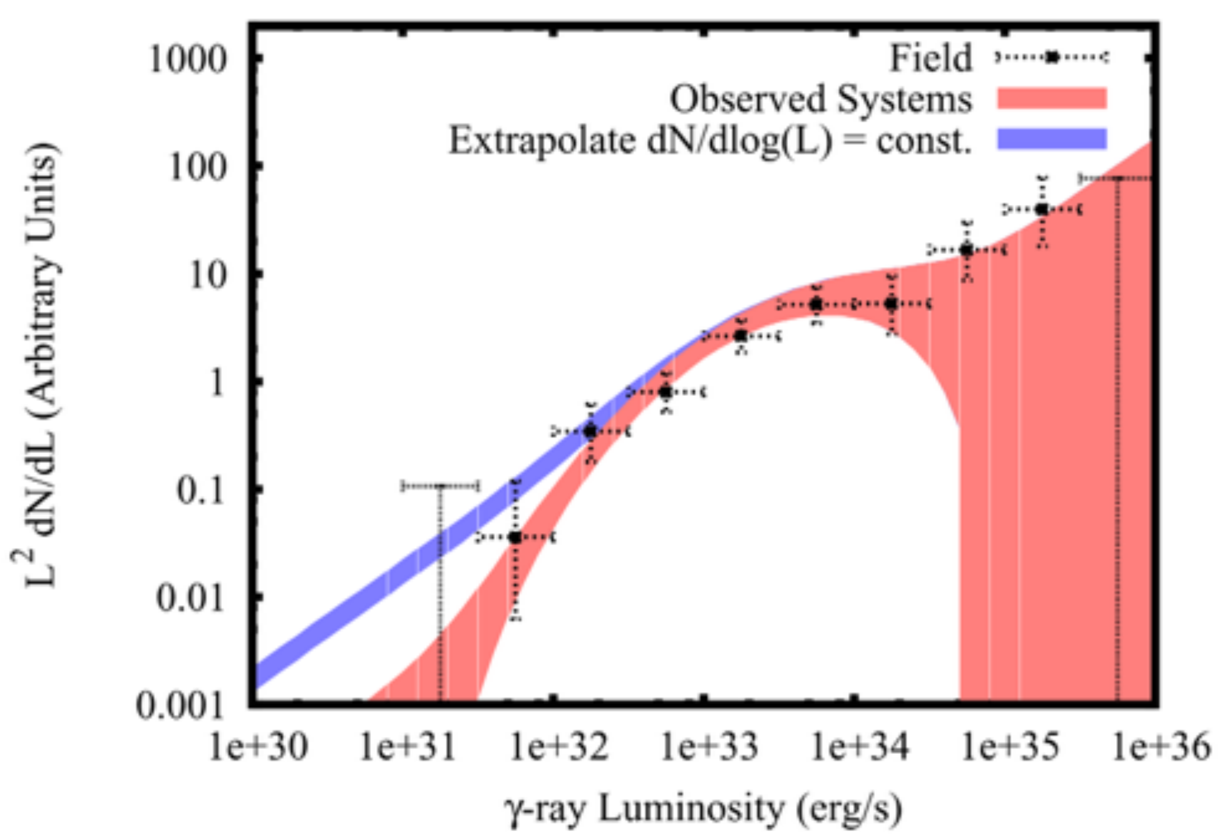
Millisecond pulsars have been discussed as a possible source of the gamma-ray excess observed from the region surrounding the Galactic Center. With this in mind, we use the observed population of bright low-mass X-ray binaries to estimate the number of millisecond pulsars in the Inner Galaxy. This calculation suggests that only ~1-5% of the excess is produced by millisecond pulsars. We also use the luminosity function derived from local measurements of millisecond pulsars, along with the number of point sources resolved by Fermi, to calculate an upper limit for the diffuse emission from such a population. While this limit is compatible with the millisecond pulsar population implied by the number of low-mass X-ray binaries, it strongly excludes the possibility that most of the excess originates from such objects.

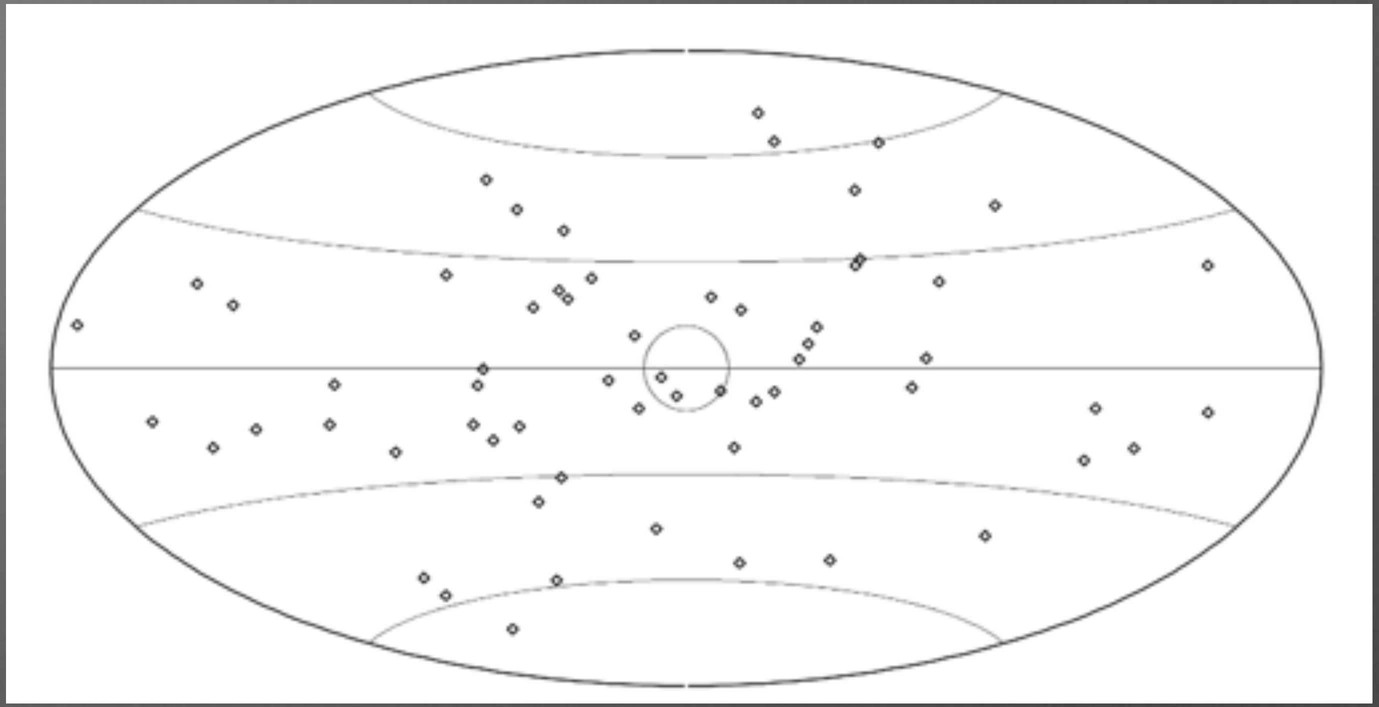
PACS numbers: 97.60.Gb, 95.55.Ka, 98.70.Rz

Millisecond Pulsars



Millisecond Pulsars





- Using the luminosity function shown here - There would need to be 226 (+91/-67) MSPs with luminosity > 10^{34} erg s^{-1} in the circular region, and 61.9 (+60/-33.7) with luminosity > 10^{35} erg s^{-1}.

- We can also compare the MSP population to the observed LMXB population. Using the ratio for LMXBs to the MSP luminosity of globular clusters, we predict that the gamma-ray luminosity in the Galactic center would imply a population of 103 (+70/-45) LMXBs in the GC, only 6 are detected

Why are Outburst Models Reasonable?

1.) Sgr A* is currently in a quiescent state, with a current luminosity 10^{-9} of the Eddington luminosity.

2.) However, evidence points towards historical outbursts

Echoes of multiple outbursts of Sagittarius A* revealed by Chandra

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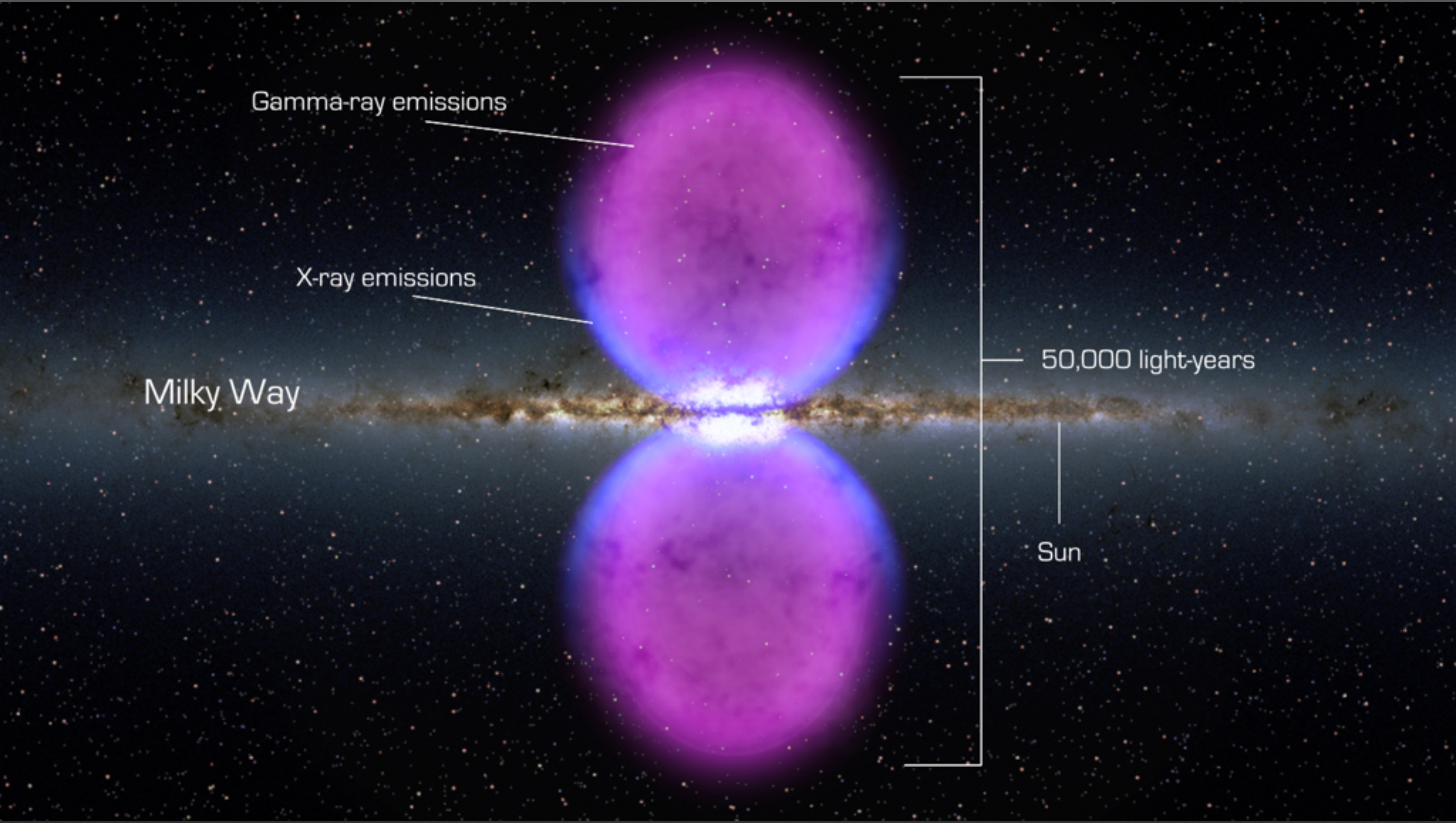
Received 8 April 2013 / Accepted 12 July 2013

ABSTRACT

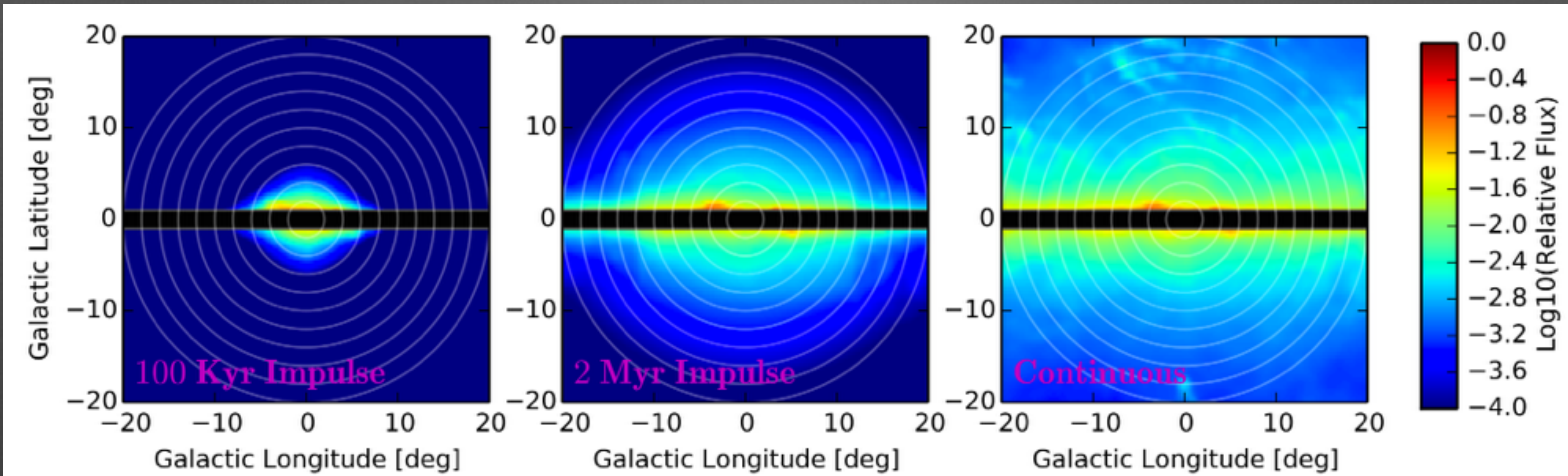
Context. The relatively rapid spatial and temporal variability of the X-ray radiation from some molecular clouds near the Galactic center shows that this emission component is due to the reflection of X-rays generated by a source that was luminous in the past, most likely the central supermassive black hole, Sagittarius A*.
Aims. Studying the evolution of the molecular cloud reflection features is therefore a key element to reconstruct Sgr A*'s past activity. The aim of the present work is to study this emission on small angular scales in order to characterize the source outburst on short time scales.
Methods. We use Chandra high-resolution data collected from 1999 to 2011 to study the most rapid variations detected so far, those of clouds between $5'$ and $20'$ from Sgr A* towards positive longitudes. Our systematic spectral-imaging analysis of the reflection emission, notably of the Fe Kα line at 6.4 keV and its associated 4–8 keV continuum, allows us to characterize the variations down to $15''$ angular scale and 1-year time scale.
Results. We reveal for the first time abrupt variations of few years only and in particular a short peaked emission, with a factor of 10 increase followed by a comparable decrease, that propagates along the dense filaments of the "Bridge" cloud. This 2-year peaked feature contrasts with the slower 10-year linear variations we reveal in all the other molecular structures of the region. Based on column density constraints, we argue that these two different behaviors are unlikely to be due to the same illuminating event.
Conclusions. The variations are likely due to a highly variable active phase of Sgr A* sometime within the past few hundred years, characterized by at least two luminous outbursts of a few-year time scale and during which the Sgr A* luminosity went up to at least 10^{39} erg s^{-1}.

Key words. Galaxy: center – X-ray: ISM – ISM: clouds

Why are Outburst Models Reasonable?



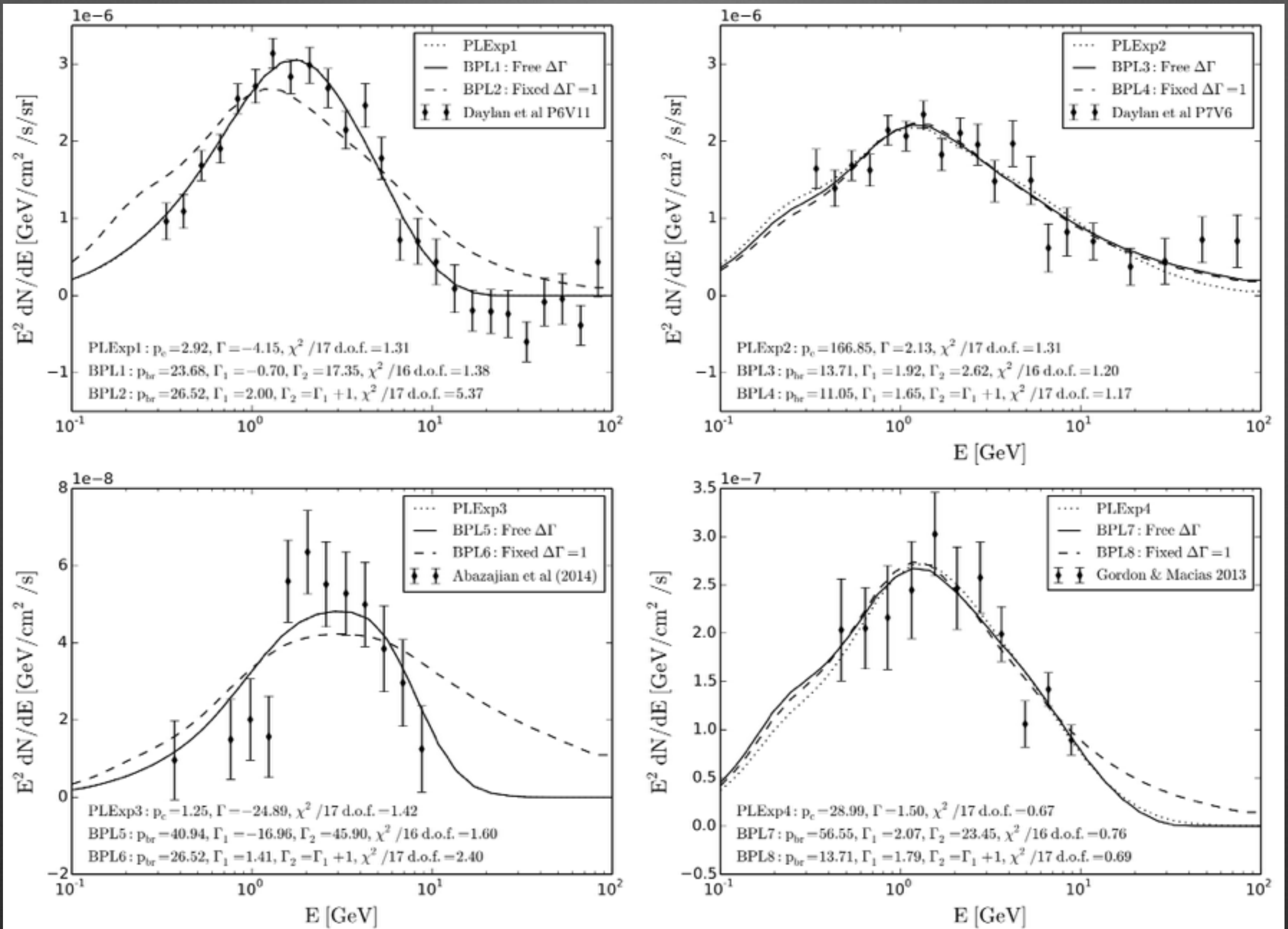
Hadronic Outbursts



Carlson & Profumo (2014)

Carlson & Profumo (2014) proposed that an outburst of protons from the galactic center could explain the spherical symmetry and spectrum of the excess

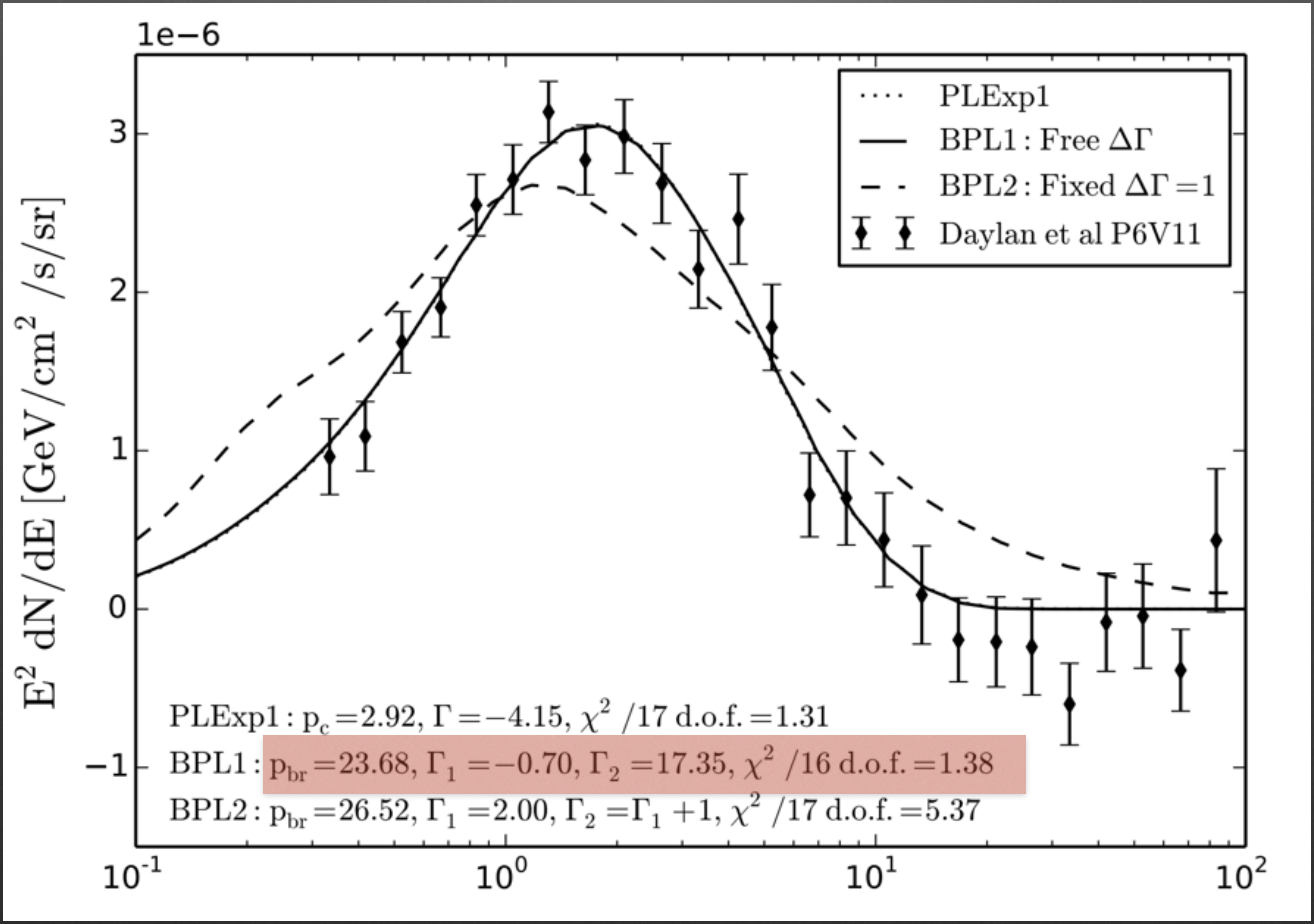
Hadronic Outbursts



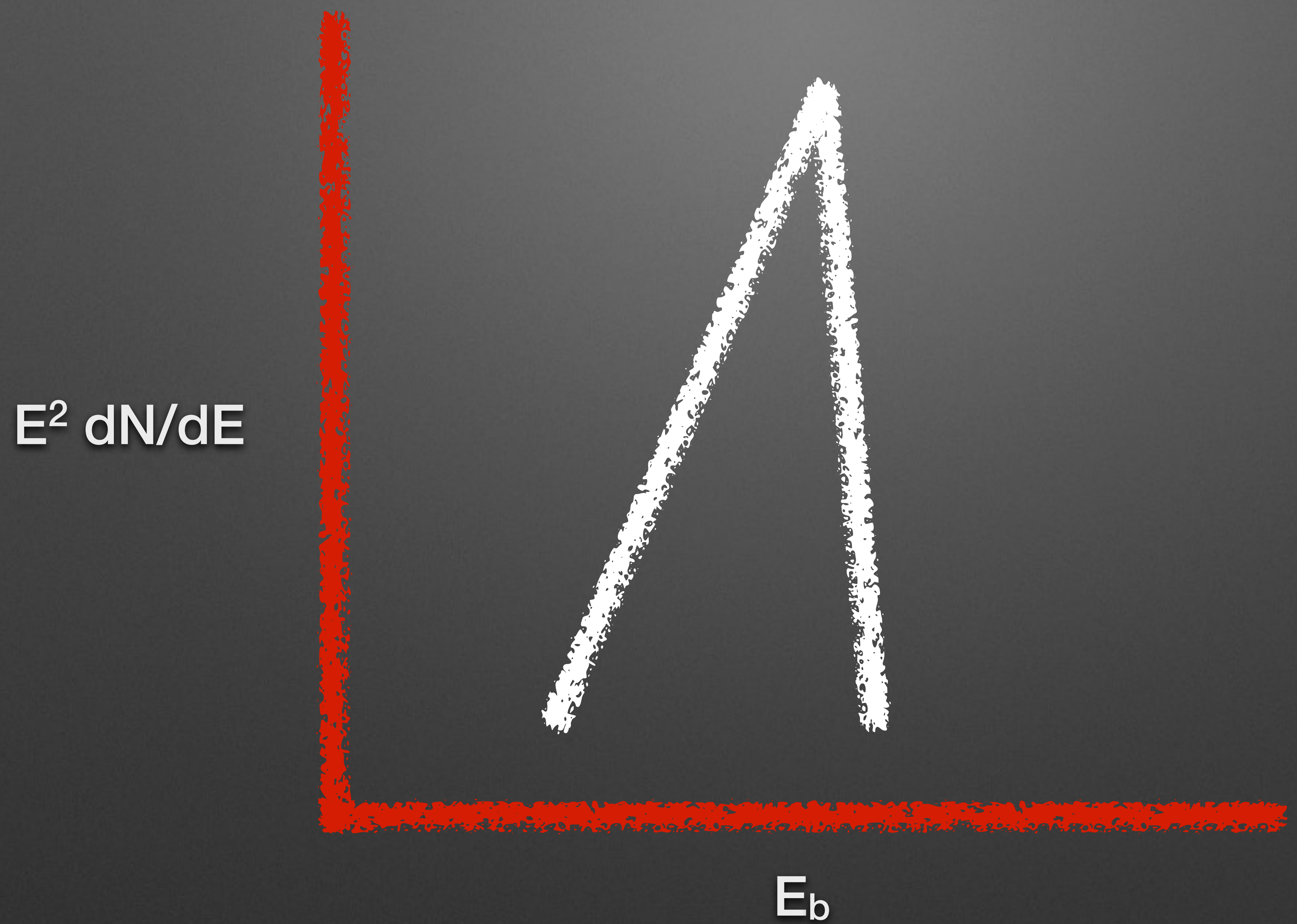
Current Models Don't Fit

- Thanks to Eric Carlson and Stefano Profumo for providing us with the Galprop output files.
- We have run these models through our code (similar to what we do with the dark matter fits). The models pick up the following TS values:
    - 0.5 kyr: **TS = 33**
    - 2.5 kyr: **TS = 43**
    - 19 kyr: **TS = 14** (with arbitrary spectrum: **TS = 26.6**)
    - 100 kyr: **TS = 0.0** (with arbitrary spectrum: **TS = 0.28**)
    - 2 Myr: **TS = 0.0**, (with arbitrary spectrum: **TS = 0.0**)
    - 7.5 Myr Continuous: **TS = 0.0** (with arbitrary spectrum: **TS = 0.0**)
    - **Linear Combination of All Hadronic Outburst Models TS = 51**
    - Dark Matter Template (Daylan et al. 2014): **TS = 315**

Current Models Don't Fit



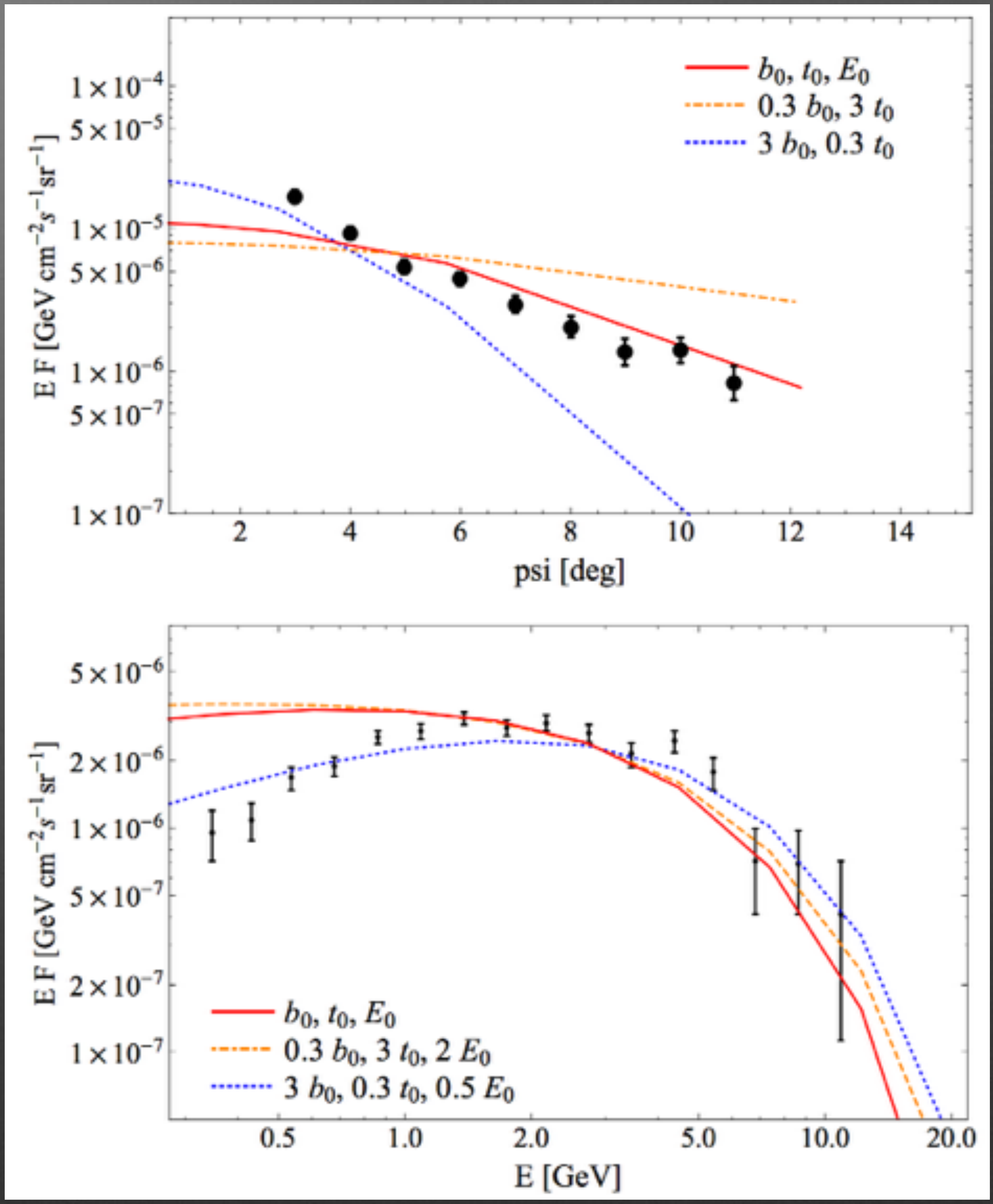
Current Models Don’t Fit



Leptonic Emission

- A peaked spectrum of cosmic-ray leptons can also produce hard emission from bremsstrahlung or inverse Compton scattering

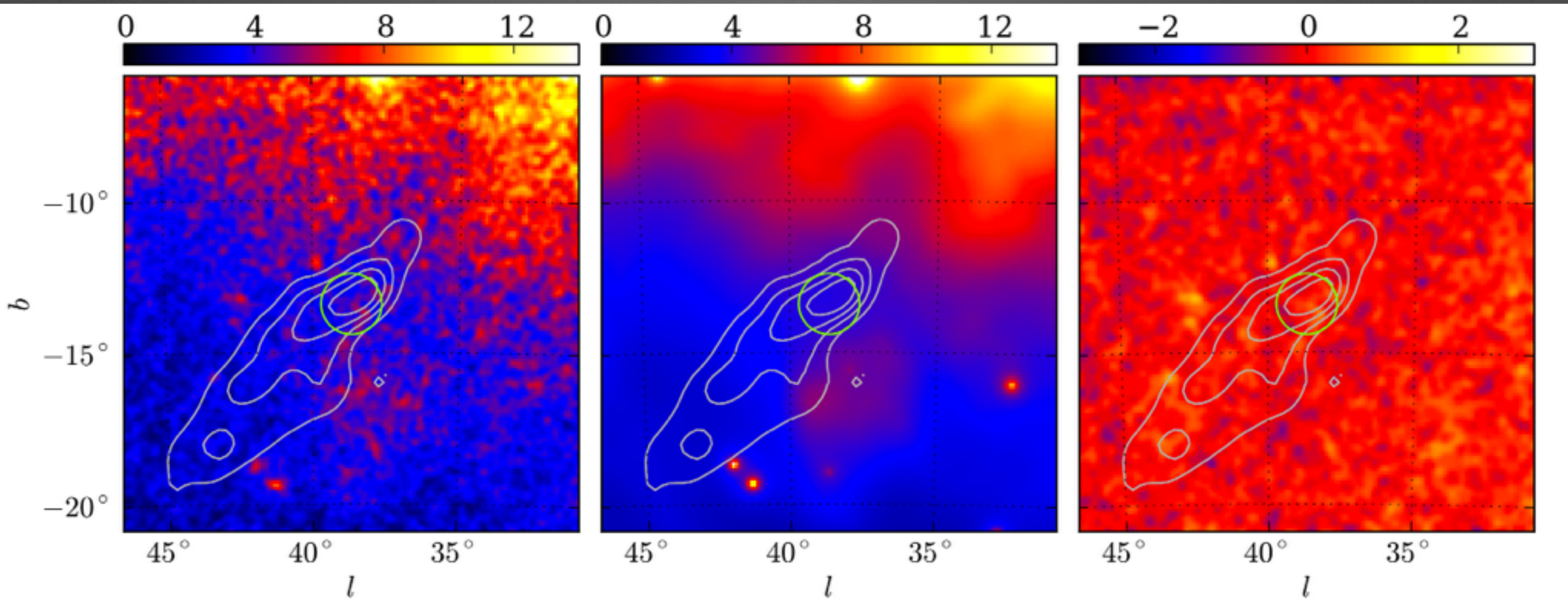
- However, electrons cool rapidly, it is difficult to produce the same hard spectrum over several degrees in the sky



Petrovic et al. (2014)

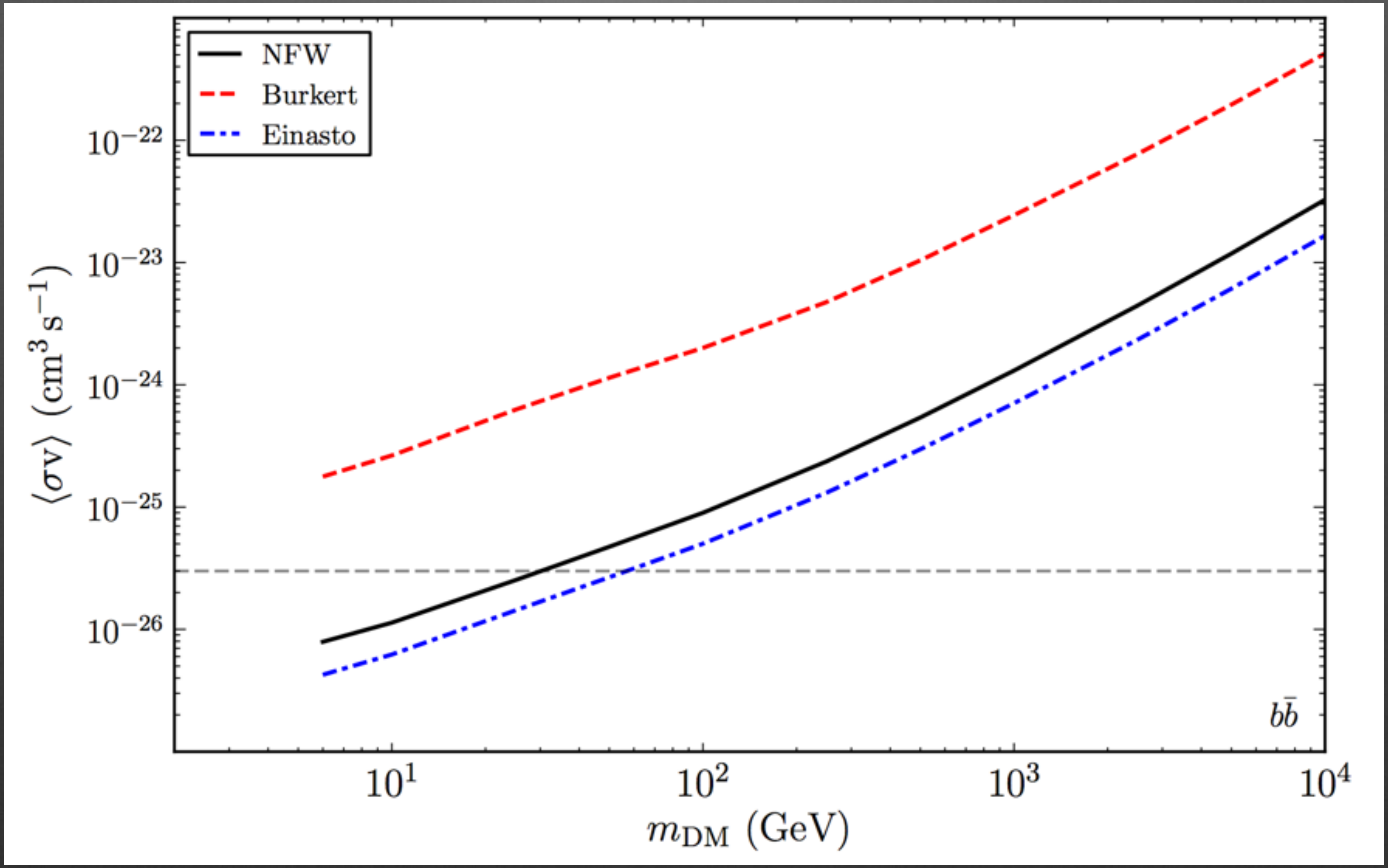
Future Indirect Tests - Smith Cloud

- Can look for new bright sources, one such possibility is High Velocity Clouds, which may be confined by a dark matter component



Drlica-Wagner et al. (2014)

Future Indirect Tests - Smith Cloud



Drlica-Wagner et al. (2014)

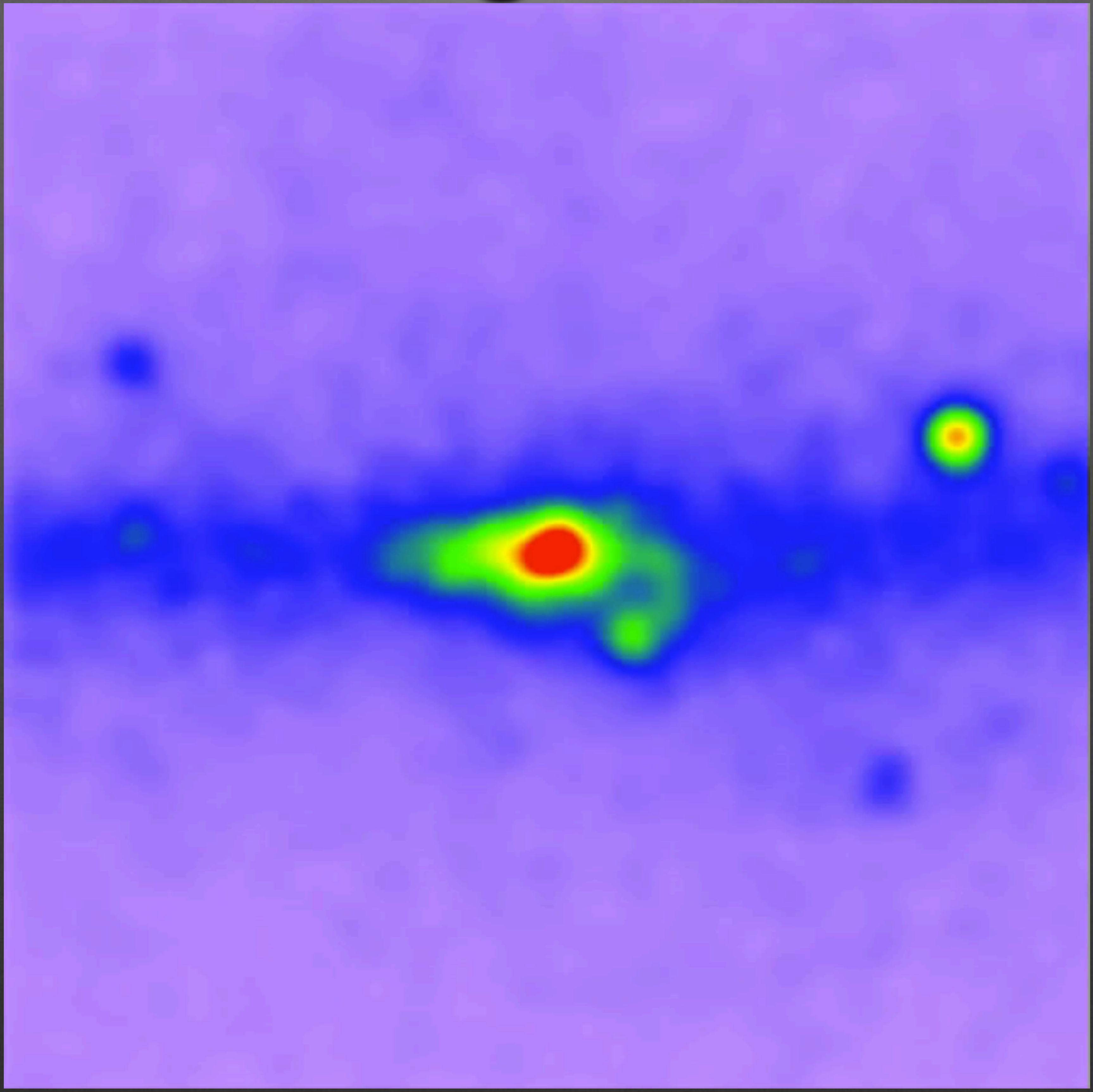
Conclusions

- The excess in emission at the galactic center (compared to diffuse models) is well established, and extremely bright

- There is no clear astrophysical interpretation of the data. In particular the hard spectrum and spherical morphology of the excess are hard to model with astrophysical templates

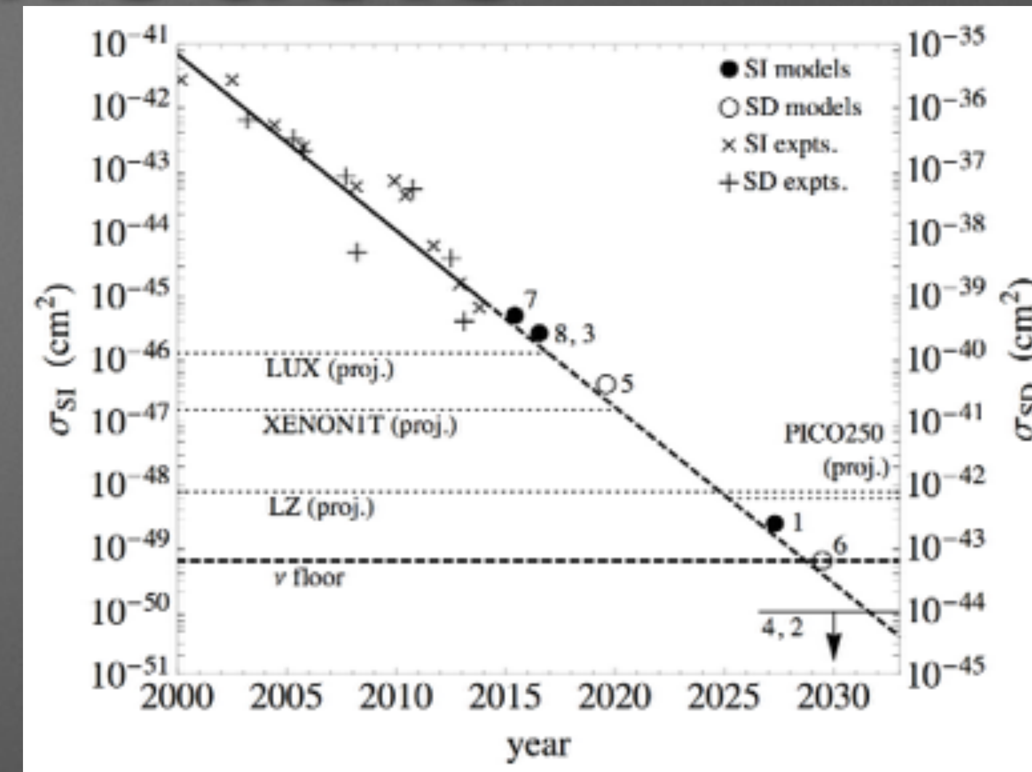
- Stay Tuned!

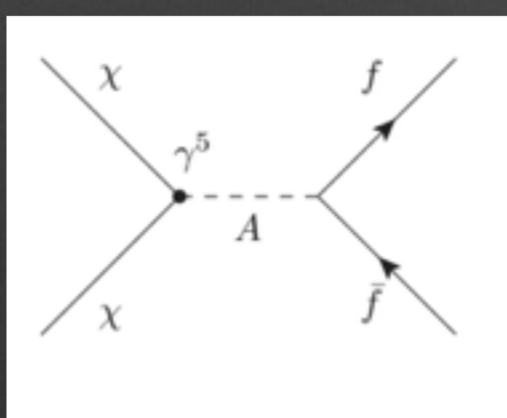
Signal!



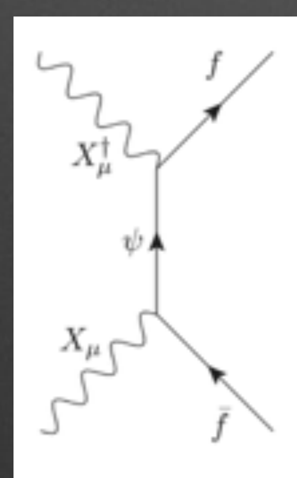
Dark Matter Models

- Many models are safe from current direct detection and collider constraints





(1)



(8)

Model Number	DM	Mediator	Interactions	Elastic Scattering	Near Future Reach? Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$ or $\sigma_{SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B_\mu^\dagger B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X_\mu^\dagger\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes

Berlin, Hooper, McDermott (2014)